Universidade de Lisboa

Instituto de Geografia e Ordenamento do Território

Propriedades da geoinformação de uso e ocupação do solo na modelação e análise ambiental

Bruno Miguel do Carmo Santana Meneses

Orientadores: Prof. Doutor Eusébio Joaquim Marques dos Reis
Prof.ª Doutora Maria José Correia Botelho Soares de Oliveira Lucena e Vale

Tese especialmente elaborada para a obtenção do grau de Doutor em Geografia, especialidade de Ciências da Informação Geográfica

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2020

… dedicada aos meus pais!

PREÂMBULO

Os cinco capítulos que compõem esta tese apresentam os conteúdos de vários artigos publicados em diferentes revistas científicas indexadas (Scopus ou ISI); e, também, os conteúdos de um artigo publicado no livro de atas de um congresso internacional (com revisão por pares). A escrita em inglês (versão inglês americano ou do Reino Unido) e a formatação varia de artigo para artigo, consoante as especificações de cada revista ou recomendações para livro de atas. Neste quadro, optou-se por se apresentar os artigos na sua forma original.

A contribuição do autor e dos respetivos coautores dos 9 artigos apresentados nos diferentes capítulos desta tese foi a seguinte:

- **Artigos do capítulo 2**

  2.2. Meneses, B.M.; Reis, E.; Reis, R.; Vale, M.J. (2018) - The effects of land use and land cover geoinformation raster generalization in the analysis of LUCC in Portugal. ISPRS International Journal of Geo-Information, 7 (10), 390, pp. 1-21. DOI: 10.3390/ijgi7100390

  Para a investigação deste artigo, os autores contribuíram da seguinte forma: conceptualização, B.M.M. (Bruno Miguel Meneses); metodologia, B.M.M.; *software*, B.M.M.; validação, B.M.M. e E.R. (Eusébio Reis); análise formal, B.M.M.; pesquisa, B.M.M. e E.R.; recursos, B.M.M.; coleção de dados, B.M.M.; escrita do artigo, B.M.M.; revisão e edição da escrita, B.M.M., E.R. e R.R. (Rui Reis); visualização, B.M.M., R.R. e M.J.V. (Maria J. Vale); supervisão, E.R. e M.J.V. Durante a investigação realizaram-se reuniões de discussão sobre o processo de estudo, com a participação de todos os autores.

  2.3. Meneses, B.M.; Pereira, S.; Reis, E. (2019a) - Effects of different land use and land cover data on the landslide susceptibility zonation of road networks. Natural Hazards and Earth System Sciences, 19, pp. 471-487. DOI: 10.5194/nhess-19-471-2019

  Neste artigo, o primeiro autor definiu o quadro conceptual de toda a investigação, recolheu os dados, analisou o estado da arte, realizou a modelação da suscetibilidade a deslizamentos e interpretou os resultados obtidos e a respetiva discussão. Susana Pereira e Eusébio Reis, leram e introduziram melhorias ao artigo. Todos os autores participaram na discussão sobre a investigação realizada nas reuniões intermédias que decorreram durante o período de investigação.

- **Artigos do capítulo 3**

3.2. Meneses, B.M.; Reis, E.; Vale, M.J.; Reis, R. (2018b) - Modeling land use and land cover changes in Portugal: a multi-scale and multi-temporal approach. Finisterra, LIII (107), pp. 3-26. DOI: 10.18055/Finis12258

O primeiro autor concebeu o quadro de análise da geoinformação do uso e ocupação do solo (UOS), calculou as respetivas alterações do uso e ocupação do solo (AUOS) e analisou os resultados obtidos. Eusébio Reis reviu o artigo, Maria J. Vale e Rui Reis fizeram alguns comentários e correções ao seu conteúdo. Todos os autores participaram na discussão realizada sobre o estudo em causa nas reuniões intermédias que decorreram durante a fase de investigação.

3.3. Meneses, B.M.; Reis, E.; Pereira, S.; Vale, M.J.; Reis, R. (2017) - Understanding driving forces and implications associated with the land use and land cover changes in Portugal. Sustainability, 9 (3), 351. DOI:10.3390/su9030351

O primeiro autor trabalhou na metodologia para a representação da geoinformação de UOS e para as análises das AUOS, concebeu o trabalho experimental e as análises estatísticas (AUOS e forças motrizes), produziu as tabelas e figuras e escreveu o artigo. Eusébio Reis, Susana Pereira, Maria J. Vale e Rui Reis leram e introduziram melhorias ao artigo. Todos os autores participaram na discussão sobre a investigação realizada nas reuniões intermédias realizadas com esse fim.

3.4. Meneses, B.M.; Reis, E.; Vale, M.J.; Reis, R. (2016a) - Modeling the probability of surfaces artificialization in Zêzere watershed (Portugal) using environmental data. Water, 8 (289), pp. 1-19. DOI: 10.3390/w8070289

O primeiro autor trabalhou na metodologia para o mapeamento do UOS, realizou todo o trabalho experimental (cálculo de probabilidades da artificialização do solo) e as análises estatísticas, produziu as tabelas e figuras e escreveu o artigo. Eusébio Reis, Maria J. Vale e Rui Reis leram e introduziram melhorias ao artigo. Todos os autores participaram na discussão sobre o estudo em causa nas reuniões realizadas.

- **Artigo do capítulo 4**

  4.2. Meneses, B.M.; Reis, E.; Vale, M.J.; Reis, R. (2018a) - Assessment of the recurrence interval of wildfires in mainland Portugal and the identification of affected LUC patterns. Journal of Maps, 14 (2), pp. 282-292. DOI: 10.1080/17445647.2018.1454351

  O primeiro autor concebeu o estudo: estruturou toda a investigação, analisou os dados (incêndios florestais e AUOS) e os resultados obtidos e preparou todo o artigo (escrita, figuras e tabelas). Eusébio Reis reviu o artigo, Maria J. Vale e Rui Reis fizeram alguns comentários sobre o seu conteúdo. Os autores discutiram o estudo em reuniões intermédias realizadas para o efeito.

- **Artigos do capítulo 5**

  5.2. Meneses, B.M.; Reis, R.; Vale, M.J.; Saraiva, R. (2015) - Land use and land cover changes in Zêzere watershed (Portugal) - water quality implications. Science of the Total Environment, 527-528, pp. 439-447. DOI: 10.1016/j.scitotenv.2015.04.092

  Neste artigo, o primeiro autor concebeu todo o quadro de investigação, analisou o UOS e os dados de parâmetros da qualidade da água, bem como os resultados obtidos. Preparou todo o artigo, nomeadamente a escrita, figuras e tabelas. Maria J. Vale, Rui Reis e Raquel Saraiva contribuíram com alguns comentários ao seu conteúdo. Todos os autores participaram na discussão sobre a investigação nas reuniões intermédias realizadas com esse fim.

  5.3. Meneses, B.M.; Reis, E.; Vale, M.J.; Reis, R. (2016b) - Urban sprawl in Zêzere watershed (Portugal) and the risk of reduction of the water quality. Proceedings of International Conference of Urban Risk (ICUR), pp. 819-826. ISBN: 978-989-95094-1-2

  O primeiro autor concebeu o quadro concetual da investigação, analisou o UOS e a variação dos parâmetros de qualidade da água (PQA), efetuou todos os cálculos de projeção das variações dos PQA e cruzou com a probabilidade de artificialização do solo, analisou os resultados e preparou todo o artigo. Eusébio Reis, Maria J. Vale e Rui Reis leram e fizeram alguns comentários acerca do seu conteúdo. Todos os autores participaram na discussão sobre o estudo realizado durante as reuniões realizadas.

5.4. Meneses, B.M.; Reis, E.; Reis, R.; Vale, M.J. (2019b) - Post-wildfires effects on physicochemical properties of surface water: the case study of Zêzere watershed (Portugal). Ribagua, 6 (1), pp. 1-15. https://doi.org/10.1080/23863781.2019.1596771

Neste artigo o primeiro autor definiu o quadro concetual da investigação, recolheu toda a bibliografia para análise do estado da arte, analisou a variação espacial e temporal dos incêndios florestais na área de estudo e cruzou os resultados obtidos com dados da qualidade da água. Também analisou os resultados obtidos neste cruzamento e preparou todo o artigo submetido à revista. Além disto, fez a revisão de acordo com os comentários dos revisores. Eusébio Reis, Rui Reis e Maria J. Vale leram, fizeram alguns comentários acerca do conteúdo do artigo e introduziram algumas melhorias. Todos os autores participaram na discussão sobre a investigação apresentada nas diversas reuniões realizadas neste âmbito.

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Em primeiro lugar, agradeço ao meu orientador, Prof. Dr. Eusébio Reis, por toda a ajuda na realização dos trabalhos apresentados, as suas recomendações, supervisão e melhorias introduzidas, tanto nos vários artigos científicos, como nesta tese.

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FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

REPÚBLICA PORTUGUESA

RESUMO

O uso e ocupação do solo (UOS) de determinados territórios têm sofrido grandes alterações nas últimas décadas, associadas quer a causas naturais, quer a causas antrópicas. Portugal não é exceção e também apresenta grandes alterações de UOS.

Do trabalho desenvolvido e que aqui se apresenta, destacam-se as consequências económicas, sociais ou ambientais que resultaram de algumas destas alterações de uso e ocupação do solo (AUOS), realçando assim a importância da sua avaliação, tanto ao nível espacial, como temporal.

As propriedades da geoinformação do UOS que integra este tipo de avaliações podem variar muito entre os diferentes conjuntos de geoinformação de UOS disponíveis, realçando-se entre elas a escala, os diferentes critérios definidos na sua produção (unidade mínima cartográfica, distância mínima entre linhas, resolução espacial, etc.), a qualidade posicional e temática, o método de recolha e a informação base.

Nesta tese apresentam-se várias avaliações de diferentes problemas ambientais utilizando geoinformação de UOS com diferentes propriedades, nomeadamente a Carta de Ocupação do Solo (COS) e a cartografia da CORINE Land Cover (CLC). As modelações espaciais realizadas foram: AUOS, forças motrizes das AUOS, probabilidade de ocorrência de incêndios florestais, probabilidade de artificialização do solo, suscetibilidade a deslizamentos, implicações ambientais na qualidade da água decorrentes das AUOS a nível geral e, em casos concretos, derivadas da expansão urbana ou da ocorrência de incêndios florestais.

Assim, o principal objetivo de todo o trabalho apresentado nesta tese é perceber se os resultados obtidos nas modelações ambientais anteriormente referidas podem variar de forma significativa consoante a geoinformação do UOS considerada, em detrimento de outra geoinformação de UOS com diferentes propriedades. Contudo, por se tratar de uma tese estruturada por artigos científicos que abordam problemáticas ambientais diferenciadas, outros objetivos são definidos caso a caso nos diferentes artigos.

As temáticas abordadas nos 9 artigos apresentados permitem vários tipos de organização da tese: abrangência espacial nacional (Portugal continental) *versus* regional (bacia hidrográfica do Rio Zêzere); objetivo metodológico centrado nas propriedades da informação *versus* comportamento dos fenómenos; divisão com base nos temas abordados (UOS; incêndios florestais; movimentos de vertente; propriedades da água). Em alguns casos a análise está

centrada exclusivamente no UOS e noutros é centrada na influência deste no comportamento de diversos fenómenos, mas também há alguns casos em que é comparada informação de UOS a diferentes escalas, enquanto noutros é utilizada a mesma informação, mas fazendo variar as suas propriedades.

Neste sentido, optou-se pela divisão da tese em 5 capítulos, tendo por base a temática principal dos artigos, conforme se apresenta em seguida, com exceção do primeiro capítulo, onde se apresenta a introdução sobre o tema principal da tese e sua estrutura.

No primeiro capítulo faz-se o enquadramento da temática em investigação, i.e., discutem-se as diferentes modelações espaciais que se podem realizar com geoinformação de UOS. Apresenta-se o resumo sobre as três dimensões da geoinformação consideradas na análise (espaço, tempo e tema), evidenciando-se nestas a crescente disponibilidade desta geoinformação ao longo dos últimos anos (componente temporal), mas também o seu detalhe. Abordam-se as questões relacionadas com as propriedades da geoinformação (por exemplo: a exatidão temática ou posicional, erros de propagação, entre outros), as formas de disponibilização e a sua manipulação. Nesta sequência, apresentam-se algumas normas ISO (*International Organization for Standardization*) com a definição de parâmetros ou especificações para a criação, disponibilização e manipulação da geoinformação. Na parte final deste capítulo apresenta-se a integração das diferentes publicações (sob a forma de artigos) com as diferentes problemáticas abordadas, todas elas integrando geoinformação de UOS na abordagem aos problemas ambientais que tratam.

No segundo capítulo apresenta-se a investigação realizada sobre a importância das propriedades da geoinformação de UOS nos resultados obtidos em diferentes modelações ambientais apresentadas em 2 artigos científicos. No primeiro artigo deste capítulo (Meneses *et al.*, 2018) apresenta-se a avaliação dos efeitos da generalização da geoinformação de UOS em conversões de vetor para *raster* na determinação das AUOS em Portugal continental. Utilizaram-se dois conjuntos de dados (*datasets*) com diferentes propriedades: CLC 2006 e 2012 e a COS 2007 e 2010. Cada *dataset* foi convertido de vetor para *raster* com diferentes resoluções (10, 25, 50, 100 e 200 m). As AUOS foram analisadas inicialmente com o vetor e depois com os *raster* nas diferentes resoluções. A análise efetuada indica que as áreas entre os mesmos tipos de UOS dos dois *datasets* em vetor não são semelhantes (embora sejam de anos diferentes, mas com períodos de diferença reduzidos), facto que pode ser explicado essencialmente pelas diferentes propriedades de cada um. Na análise das AUOS obtidas com os *raster* observou-se que elevadas resoluções têm resultados muito idênticos aos obtidos com o vetor, mas esta relação vai diminuindo exponencialmente com o aumento do tamanho das células. Os resultados das AUOS obtidas com os *raster* de resolução superior a 100 m evidenciam diferentes tendências de AUOS, face a resultados obtidos com *raster* de resolução inferior, ou mesmo com o vetor. Os resultados obtidos com os *raster* evidenciam os diferentes efeitos da *amalgamation* e *dilation* que ocorrem no processo de conversão vetor-*raster*, efeitos mais visíveis em reduzidas resoluções, mas também outros fatores como a forma e a área dos polígonos. Os resultados obtidos são importantes para futuras avaliações de AUOS com geoinformação em estrutura *raster*, pois as diferentes propriedades da geoinformação considerada na modelação podem explicar diferentes resultados que se pode obter neste tipo de avaliação. No segundo artigo (Meneses *et al.*, 2019a) apresenta-se a modelação da suscetibilidade a deslizamentos na bacia hidrográfica do Rio Zêzere, mais concretamente o zonamento da suscetibilidade da rede de estradas utilizando o método do Valor Informativo. Neste caso, utilizou-se um conjunto de variáveis (fatores condicionantes) que permaneceu estável, variando apenas a introdução da geoinformação de UOS (COS ou CLC). Os resultados obtidos permitiram perceber que há efetivamente variações consoante as diferentes propriedades da geoinformação de UOS que integrou a modelação, sendo os resultados obtidos pela COS mais detalhados e os que permitem identificar com maior precisão os locais das estradas onde há maior probabilidade de ocorrer os próximos movimentos de vertente.

No terceiro capítulo faz-se a análise das AUOS a diferentes escalas e a avaliação das forças motrizes destas AUOS, sendo esta análise apresentada em 3 artigos científicos. No primeiro artigo deste capítulo (Meneses *et al.*, 2018b) apresenta-se a modelação das alterações de UOS em Portugal, utilizando uma abordagem multiescala e multitemporal. Este estudo apresenta avanços na análise destas alterações (de 1990 a 2012) utilizando a cartografia mais recente à data da publicação do artigo para o território português (cobertura integral), mas também um conhecimento inovador que ajuda a perceber essas alterações. As tendências de variação espacial dos vários tipos de UOS não são constantes ao longo do tempo, revelando as diferentes dinâmicas espaciais e temporais destas alterações no território em análise. A estimativa das futuras alterações de UOS foi também realizada com recurso a autómatos celulares (CA-Markov). No segundo artigo (Meneses *et al.*, 2017) apresenta-se a avaliação das AUOS, considerando os grandes tipos de UOS de Portugal continental, e identificaram-se algumas forças motrizes destas alterações. Neste sentido, quantificou-se a área por cada tipo UOS no território para os anos de 1995, 2007 e 2010, e faz-se a avaliação das AUOS ao nível das NUTS II. As variações de área por UOS são cruzadas com alguns indicadores socioeconómicos e ambientais para identificação das forças motrizes das AUOS observadas.

Os resultados desta análise apontam no sentido de que as AUOS são diferenciadas por cada NUTS II considerando a variação relativa de área por cada tipo de UOS, destacando-se em termos absolutos a perda de floresta na Região Centro de Portugal. O aumento da artificialização do solo também se destaca na análise efetuada, sobretudo para solos agrícolas e florestais. No entanto, as AUOS diferem consoante o período em análise, destacando-se como causas indutoras da mudança as medidas, políticas e investimentos associados a cada período. No terceiro artigo (Meneses *et al.*, 2016a) apresenta-se a determinação da probabilidade de artificialização do solo (PAS) na bacia hidrográfica do Rio Zêzere (Portugal). Nesta bacia hidrográfica observaram-se grandes alterações de uso e ocupação do solo nas últimas décadas, destacando-se as transições de vários tipos de UOS para solos artificializados. Esta probabilidade foi determinada com recurso a métodos estatísticos (Lógica Fuzzy e Valor Informativo), utilizando geoinformação biofísica. A variável dependente neste caso é o UOS (áreas artificializadas), sendo utilizada geoinformação da CLC 1990 para a modelação e da CLC 2012 para validação (apenas a área de acréscimo entre 1990 e 2012). Os resultados obtidos por cada método foram avaliados independentemente, sendo elaborado para cada um as curvas de sucesso, com a respetiva determinação da área abaixo da curva (AAC). Os resultados obtidos pelo método Fuzzy Gamma apresentam maior eficiência na determinação da PAS.

No quarto capítulo (Meneses *et al.*, 2018a) apresenta-se a avaliação da ocorrência de incêndios florestais em Portugal continental desde 1975 até ao primeiro semestre de 2017. O intervalo de recorrência dos incêndios florestais foi avaliado e, a partir destes resultados, identificaram-se os padrões de UOS mais afetados por este tipo de eventos. Desta investigação resultou também a elaboração de um mapa de probabilidade de ocorrência de incêndios florestais. Este mapa aponta as regiões Norte e Centro como as de maior probabilidade de ocorrência, sendo estas as regiões onde se observou a maior frequência de grandes incêndios florestais. Quanto aos padrões de UOS mais afetados por este tipo de eventos, sobressai a ocupação por *Pinus pinaster*, *Eucalyptus globulus* e matos. Os resultados obtidos são importantes sobretudo para o planeamento e gestão do território, já que o conhecimento dos locais com maior probabilidade de ocorrência de incêndios florestais permite a criação de medidas preventivas e reativas, bem como o acompanhamento da sua implementação efetiva.

No quinto capítulo aborda-se a questão das AUOS e as implicações que estas têm na qualidade da água, temática desenvolvida nos três artigos científicos aqui apresentados. No primeiro artigo deste capítulo (Meneses *et al.*, 2015) apresenta-se a interferência das AUOS na qualidade da água superficial das principais albufeiras presentes na bacia hidrográfica do

Rio Zêzere. Esta investigação parte também das grandes AUOS aqui observadas nas últimas décadas, mas neste caso avaliaram-se alguns impactes ambientais que daí resultaram, nomeadamente o arrastamento de elementos químicos e compostos pela água de escorrência superficial proveniente de áreas agrícolas, áreas queimadas resultantes dos incêndios florestais e também água utilizada para as atividades antrópicas (resíduos industriais e domésticos). Estabeleceram-se correlações entre as AUOS e as variações de alguns parâmetros físico-químicos da água superficial (dados de várias estações de qualidade da água localizadas na bacia hidrográfica). Na avaliação das AUOS evidencia-se a perda de floresta (sobretudo de coníferas) e o aumento de solos ocupados por matos, estando estas AUOS relacionadas com o aumento do pH da água; enquanto o aumento de solos artificializados e solos utilizados para a pastorícia apresentaram relação positiva com o aumento do teor de sais solúveis e coliformes fecais na água. No segundo artigo (Meneses *et al.*, 2016b) utiliza-se as AUOS identificadas na bacia hidrográfica do Rio Zêzere para a avaliação do risco de redução da qualidade da água superficial, nomeadamente associado à expansão urbana para solos ocupados por outros tipos de UOS (facto observado a partir da análise da CLC de vários anos). Este tipo de AUOS tem interferência na qualidade da água, facto demonstrado na bacia hidrográfica em estudo, nomeadamente na água da albufeira de Castelo de Bode. Neste capítulo apresenta-se também a determinação da probabilidade de expansão urbana, utilizando um método estatístico bivariado (Lógica Fuzzy – operador Gamma). Utilizando a cartografia CLC anteriormente referida, determinou-se a tendência de aumento de solo artificializado até 2018 e para 2024. O mesmo procedimento foi realizado com alguns parâmetros físico-químicos da água superficial, i.e., com as observações registadas no passado, determinou-se a tendência de variação de concentração dos parâmetros físico-químicos considerados para o mesmo período, incluindo-se nesta análise a variação de área artificializada (observada e estimada). Os resultados obtidos indicam que o aumento de área artificializada, sob as mesmas condições em que ocorreram no passado, terá implicações negativas na qualidade da água, servindo o mapa com a probabilidade de artificialização do solo para auxiliar a definir medidas de prevenção associadas a este tipo de UOS, sobretudo nas imediações dos cursos de água principais. No terceiro artigo (Meneses *et al.*, 2019b) aborda-se a problemática da alteração das propriedades físico-químicas da água após a ocorrência de incêndios florestais na bacia hidrográfica do Rio Zêzere. Para o efeito, também se dividiu a bacia hidrográfica em setores em função da localização dos principais corpos de água com estações de monitorização da qualidade da água. Os resultados demonstraram haver ligação, enquanto causa-efeito, entre a ocorrência dos incêndios florestais e a alteração das propriedades físico-químicas da água.

PALAVRAS-CHAVE: Propriedades da geoinformação do uso e ocupação do solo; alterações de uso e ocupação do solo; modelação ambiental; qualidade da água; incêndios florestais; suscetibilidade a deslizamentos de vertente.

ABSTRACT

In mainland Portugal, large land use and land cover (LUC) changes (LUCC) have occurred in recent years, especially in forested and agricultural lands. In general, the spatiotemporal LUCC have been very diverse in this territory. Some LUC classes featured high reductions in area in one period but, in subsequent periods, revealed that the reductions slowed, or vice versa. On the other hand, it was observed that the LUCC were not spatially proportional.

The afore mentioned differences are a product of different driving forces on the LUCC and catastrophic events, such as wildfires. For driving forces, it is necessary to highlight the LUCC of agriculture land derived from the construction of dams (Alentejo region) or the conversion of coniferous forest into eucalyptus forest (Center region) associated with an increased gross value and employment in industry and forestry.

The wildfires in the Portuguese territory are responsibly for great LUCC in forest areas, events that caused catastrophic consequences (human and environmental). The Center and North regions are the most affected, but these also presented the highest percentage of forested area relative to other regions. The incidence of wildfires is most significant in the Center, where the largest wildfires also occurred in the past years, especially in the eucalyptus and *Pinus pinaster* forests.

Another consequence of LUCC is the reduction of the superficial water quality, a fact verified in the dams of the Zêzere watershed (center of Portugal). Here, water reservoirs located in the sub-basins with greater forest area lead to higher water quality protection. On the other hand, anthropic actions are the main driving forces inducing land use change, for example, forest area transitions to another type of LUC, e.g., transitions to agricultural soils or artificial soils induce water stress, increasing the risk of water quality deterioration. In general, it was verified that surface water degradation is caused by surface runoff from artificial and agricultural areas, wildfires and burned areas, and derived by sewage discharges from agroindustry and urban sprawl. Some measures should be applied in the territory where these LUCC directly influenced the quality of the water (e.g., reforestation, restriction in water bodies surrounding urban construction, or the application of agriculture chemical products).

In this context, it is necessary to highlight the LUC geoinformation characteristics because different results were observed when using LUC geoinformation with different properties. Also, the analyses of results when LUC geoinformation is converted from vector to raster is important because different resolutions give different LUCC results, and consequently, different conclusions.

With the use of more detailed LUC geoinformation in different modeling, in this case, the Portuguese Land Cover Map (COS), the results obtained are more detailed and present more agreement and accuracy, e.g., the landslide susceptibility zonation of the road network. However, when the modeling is performed using LUC data in raster with different resolutions, different LUC areas are obtained for the Portuguese territory—results derived from a high generalization of this geoinformation in the vector-to-raster conversion and also the occurrence of the amalgamation and dilation processes; while the CORINE Land Cover (CLC) comprises LUC geoinformation more generalized compared to the COS geoinformation, these processes are not self-evident in high resolutions.

The present thesis aims the assessment of the LUCC at regional (the Zêzere watershed) and national scales, using LUC geoinformation with different properties to identify variations in results of different environment modeling. Using the COS and/or the CLC (datasets with different properties), the following modeling were performed: LUCC, driving forces of LUCC, landslide susceptibility, wildfires occurrence, surface artificialization, and water quality variation. However, this thesis is structured by different scientific articles that deal different environmental issues, other specific objectives are defined on a case-by-case in the different articles.

Thus, the first chapter presents the framework of the thematic research, i.e., the specifications, concepts, and different spatial modeling that can perform with LUC geoinformation. It also presents the integration of the different publications (papers) with the various issues addressed.

The second chapter presents the evaluation the influence of the LUC geoinformation with different properties in results of different environment modeling presented in 2 scientific articles. The first article (Meneses *et al.*, 2018) of this chapter presents the assessment of the effects of LUC data generalization that occur in vector-to-raster conversions. The LUCC in mainland Portugal was performed using the COS and CLC in different resolutions and with vector data. The LUCC results show different trends between higher and lower resolution, but also between the two LUC datasets. The second article (Meneses *et al.*, 2019a) evaluated the influence of LUC geoinformation with different properties on landslide susceptibility (LS) zonation of the road network in the Zêzere watershed (located in the Central region of Portugal). The Information Value Method was used to assess LS using two models: one including detailed LUC geoinformation (COS) and other including more generalized LUC geoinformation (CLC). The LS results obtained in both models present a high accuracy in terms of the area under curve (>90 %), but the model obtained with more detailed LUC data produces better results in the LS zonation on the road network.

In the third chapter presents the LUCC modeling at different scales and the driving forces was evaluated, researches presented in 3 scientific articles. First article of this chapter (Meneses *et al.*, 2018b) presents the LUCC modeling in mainland Portugal, using a multi-scale and multi-temporal approach. The results show advances in the analysis of LUCC (from 1990 to 2012, and a projection to 2027) using the most recently cartography of the Portuguese territory (full coverage) but also the discussion about the past and future LUCC. In the second article (Meneses *et al.*, 2017), the evaluation of the LUCC was performed, considering the main LUC types of mainland Portugal, and the main driving forces of the LUCC was identified (by NUTs II). LUCC are different depending on the period and region assessed, reflecting the measures, policies, and investments applied. In the third article (Meneses *et al.*, 2016a), the determination of the probability of artificialization in the Zêzere watershed (Portugal) was accomplished, using statistical methods (Fuzzy Logic and Information Value Method) and environmental data.

The fourth chapter (Meneses *et al.*, 2018a) presents the evaluation of the wildfires occurrences in mainland Portugal between 1975 and the first half of 2017, resulting in a map with the probability of wildfire occurrence (PWO). The return period of wildfires was assessed, and, by the PWO results, the LUC patterns most affected by wildfires were identified.

In the fifth chapter the LUCC and the interferences on water quality was evaluated, research presented in 3 scientific articles. The first article of this chapter (Meneses *et al.*, 2015) presents the assessment of the impacts of LUCC on the water quality of the Zêzere watershed's main reservoirs, mainly in the surface water degradation caused by surface runoff from artificial and agricultural areas, wildfires and burned areas, and caused by sewage discharges from agroindustry and urban sprawl. In second article (Meneses *et al.*, 2016b), the LUCC identified in the Zêzere watershed was used to assess the risk of the reduction quality of surface water, mainly derived from urban sprawl to land occupied by other types of LUC. The third article (Meneses *et al.*, 2019b) presents an analysis of the temporal and spatial occurrence of wildfires within the Zêzere watershed. It was observed that the extent of the burned areas has a high annual variation and is not directly related to the number of reported occurrences. Environmental stress was observed derived of these events, especially on the surface water quality. Thus, variations in the physicochemical properties of the surface water was analyzed, depending on the occurrence of wildfires and their corresponding burned areas. The increase of certain water quality parameters downstream of watercourses that intersect sub-basins with burned areas demonstrates the straight relation between wildfires and an increasing risk for water quality.

KEYWORDS: Properties of land use and land cover geoinformation; land use and land cover changes; environment modeling; water quality; wildfires; landslides susceptibility.

Índice

Índice de figuras

Nota: este índice não inclui as figuras que são apresentadas nos diversos artigos.

Índice de tabelas

Nota: este índice não inclui as tabelas que são apresentadas nos diversos artigos.

ABREVIATURAS E ACRÓNIMOS

AUC	Area under the curve
AUOS	Alteração de uso e ocupação do solo
BGRI	Base Geográfica de Referenciação da Informação
CDG	Conjuntos de dados geográficos
CLC	CORINE Land Cover
COS	Carta de Ocupação do Solo
CSW	Catalogue Services for the Web
DGT	Direção Geral do Território
EEA	European Environment Agency
EFFIS	European Forest Fire Information System
EU	European Union
GI	Geoinformation
GIS	Geographic Information System
GVA	Gross value added
ICNF	Instituto da Conservação da Natureza e das Florestas
IGEOE	Instituto Geográfico do Exército
IPMA	Instituto Português do Mar e da Atmosfera
ISA-UL	Instituto Superior de Agronomia – Universidade de Lisboa
ISO	International Organization for Standardization
IV	Information Value
IVV	Instituto da Vinha e do Vinho
LOD	Linked Open Data
LS	Landslide susceptibility
LUC / LULC	Land use and land cover
LUCC / LUCCs	Land use and land cover changes
MAP	Mean Annual Precipitation
NUTS	Nomenclature of territorial units for statistics
PAS	Probabilidade de artificialização do solo
PCA	Principal Components Analysis
PQA	Parâmetros de qualidade da água
PWO	Probability of wildfire occurrence
REN	Reserva Ecológica Nacional
RMSE	Root Mean Square Error
ROC	Receiver operating characteristic
SIG	Sistemas de informação geográfica

SNIG	Sistema Nacional de Informação Geográfica
SNIRH	Sistema Nacional de Recursos Hídricos
UOS	Uso e ocupação do solo
USGS	United States Geological Survey
WCS	Web Coverage Services
WFS	Web Feature Service
WMS	Web Map Service
WMTS	Web Map Tile Service
WPS	Web Processing Services
WQP	Water quality parameters

Capítulo 1

GEOINFORMAÇÃO DO USO E OCUPAÇÃO DO SOLO (UOS): PROPRIEDADES, DISPONIBILIDADE E ANÁLISE DAS ALTERAÇÕES DE UOS E SUAS IMPLICAÇÕES

1.1. A GEOINFORMAÇÃO DE USO E OCUPAÇÃO DO SOLO

1.1.1. PROPRIEDADES DA GEOINFORMAÇÃO

Para o estudo de fenómenos espaciais, onde se incluem as alterações de uso e ocupação do solo (AUOS), existe atualmente uma miríade de fontes de geoinformação. Porém, a informação geográfica geralmente apresenta incerteza, que pode ser de natureza semântica ou posicional. Toda a informação passível de espacialização é também designada por geoinformação (abreviatura de informação geográfica). Goodchild (2009) refere que informação geográfica é definida como sendo a informação que vincula locais na superfície da Terra, ou perto da mesma, a propriedades desses mesmos locais.

Goodchild (2018) descreve dois aspetos que se diferenciam quanto à incerteza da geoinformação: 1.º - a determinação da localização é um problema na medição, pois como todas as medições, está sujeita a erros do instrumento de medição, e para o qual este autor apresenta o exemplo de um GPS portátil típico, como a aplicação e dispositivo instalado na maioria dos *smartphones*, em que se pode atingir uma precisão de medição de aproximadamente 10 m, mas na prática esta precisão pode ser afetada negativamente sob pontes e túneis, em prédios, em canhões urbanos e sob densas copas de árvores, mas refere também que as medições de latitude e longitude são obtidas em relação ao *datum* geodésico, que pode mudar de tempos em tempos, e também podem ser afetadas por movimentos da crusta; 2.º - muitos tipos de geoinformação são afetados por incertezas e ambiguidades de definição, dando o exemplo da referência a um local residencial em que o mesmo é definido pela latitude e longitude através de um ponto, onde não se sabe exatamente a localização deste ponto, será a porta da frente ou a caixa de correio na estrada rural que pode estar a várias centenas de metros da porta da frente da casa? O que significa exatamente "urbano" num mapa de uso do solo, e a partir de que limite passa a rural? Assim, este autor refere que estas questões de incerteza semântica podem ter maiores impactos na análise e modelação, do que questões de incerteza posicional.

Neste contexto, importa em primeiro lugar analisar e perceber questões concetuais ligadas à natureza da geoinformação, conhecimento fundamental para que se entendam os resultados que se podem obter a partir da mesma.

Vários métodos são usados para reduzir um fenómeno geográfico para duas estruturas que podem ser codificadas em bases de dados, sendo elas o vetor e o *raster* (Longley *et al.*, 2005). O *raster* representa-se por células, também chamadas de pixéis (embora este termo deva ser utilizado apenas para designar informação obtida de forma remota), e todas têm atributos que permitem representar a variação geográfica de um fenómeno. Normalmente estas células são quadrados, mas existem outras formas geométricas, como os triângulos, hexágonos ou os octógonos (Campbell e Shin, 2012). Já o vetor, usa elementos discretos para representar a geometria do mundo real através de linhas, pontos e polígonos (Bolstad, 2012). Ambas as formas de representação integram a designada geoinformação.

A geoinformação inclui três dimensões, segundo Veregin (1998): espaço, tempo e tema (onde - quando - o quê). Segundo este autor, a dimensão espacial inclui a consistência topológica ou regras topológicas, a dimensão temporal é referente à topologia temporal, i.e., um determinado evento só pode ocorrer num determinado momento e a dimensão temática inclui a redundância de atributos temáticos. Estas três dimensões são a base para todas as observações geoespaciais (Berry, 1964; Sinton, 1978), mas também a base para a avaliação da qualidade da geoinformação, incluindo-se aqui diversas componentes como a exatidão, precisão, consistência e completude (Veregin, 1998). As diferentes causas e os diferentes tipos de imprecisão também são discutidos por Veregin (1999).

Em termos gerais, a qualidade da geoinformação é fundamental para se obter bons resultados nas análises realizadas através dos Sistemas de Informação Geográfica (SIG) ou via serviços Web que utilizam este tipo de geoinformação (Joos, 2006).

Fazendo parte dos SIG as componentes "recolha", "armazenamento", "manipulação" e "apresentação de informação geográfica", o recurso a estas tecnologias proporciona soluções práticas no estudo e perceção de determinados processos que ocorrem no território (Lenzi, 1997), mas também permitem avaliar erros associados à geoinformação, por exemplo erros topológicos, exatidão posicional, temáticos, entre outros.

A exatidão (em inglês *accuracy*) da informação é entendida por muitos como uma "medida da qualidade da informação", mas esta é o inverso do erro, constituindo-se apenas como uma componente da qualidade (Veregin, 1998). Esta componente baseia-se nas entidades (fenómenos do mundo real), atributos (propriedade relevante) e valores (medidas quantitativas e/ou qualitativas).

A exatidão espacial, i.e., a exatidão da componente espacial, está ligada essencialmente às *geodatabases* ou bases de dados geográficas, onde são consideradas métricas em função da dimensionalidade das entidades, por exemplo, no caso dos pontos, são consideradas as dimensões horizontal, vertical e total (x, y, z) (Goodchild, 1991).

A exatidão temática é a exatidão dos atributos/valores codificados numa base de dados, estando esta métrica muito dependente da escala dos dados. Neste tipo de exatidão, Veregin (1998) descreve que para os dados quantitativos (e.g. precipitação), o seu tratamento pode ser obtido com uma coordenada z (e.g. elevação) e a avaliação pode basear-se numa métrica que inclui o erro vertical (*Root Mean Square Error* – RMSE); enquanto para os dados qualitativos, normalmente estes são avaliados por tabelas de confusão ou de transição (*cross-tabulation*), resultando numa matriz de erros.

No caso da geoinformação de uso e ocupação do solo (UOS) há metodologias de avaliação temática baseadas nas tabelas de confusão (Jiang *et al*., 2014; Shi *et al*., 2000; Zhang *et al*., 2014), em que são cruzados conjuntos de dados temáticos de diferentes momentos, ou cartografia com informação com diferentes propriedades (e.g. geoinformação obtida com diferentes métodos de recolha), para se quantificar diferenças entre os diferentes conjuntos de geoinformação e apurar, por exemplo, erros de produção (Congalton e Green, 2009).

A escala da geoinformação é importante na modelação espacial, pois o seu detalhe pode fazer variar os resultados, facto explicado pelo grau de generalização que cada conjunto de geoinformação possa apresentar. A escala adotada na elaboração de uma determinada cartografia pode ser variável e esta pode ser diferente da escala da geoinformação disponibilizada como produto final, ou seja, pode haver generalização da geoinformação relativamente ao detalhe inicialmente definido na sua elaboração. Como referido por Goodchild (2001), o termo escala tem muitos significados, alguns dos quais sobreviventes da transição de representações da informação analógica para digital. Refere também que, em termos específicos, a métrica primária da escala na cartografia tradicional (a fração representativa), não tem um significado bem definido para dados digitais, sendo mais significativo para estes dados a extensão espacial e a resolução espacial (i.e., a sua proporção), onde a relação comprimento/escala é adimensional.

Assim, outra componente importante na avaliação da qualidade da geoinformação é a resolução (Goodchild, 2001; Veregin, 1998). Esta também é entendida como precisão, numa perspetiva de que pode fazer variar o detalhe da geoinformação, sendo assim finita, porque nenhum sistema de medição é infinitamente preciso, admitindo-se assim que as bases de dados são intencionalmente concebidas com especificação de generalização de dados (Veregin e Hargitai, 1995). Nesta componente destaca-se a resolução temática referente à precisão das medições ou categorias para um determinado tema (Veregin, 1998).

Na avaliação da qualidade da geoinformação também se pode referir a completude, um termo que se refere à falta de erros de omissão numa base de dados. A completude é avaliada relativamente às especificações da base de dados, onde se define o grau pretendido de generalização e abstração (omissão seletiva) (Brassel *et al.*, 1995).

Contudo, Goodchild (2018) refere que toda a geoinformação está sujeita à incerteza, sendo impossível que qualquer item de geoinformação seja perfeito quanto à sua exatidão, assim como perfeitamente reprodutível.

A compreensão necessária por parte dos utilizadores sobre as propriedades da geoinformação e os fatores que influenciam a utilização da mesma em diversos contextos (e.g. performance da tecnologia utilizada), é essencial para o desenvolvimento de produtos de qualidade ou análises espaciais com o mínimo de erros possíveis (Harding, 2013).

A criação de normas ISO (International Organization for Standardization) sobre informação geográfica (disponíveis em http://www.iso.org/iso/home.htm) vem, de certa forma, definir orientações padrão de âmbito internacional sobre terminologia, perfis, estruturas, referências, entre outros parâmetros ou especificações que esta informação deve obedecer, tanto na sua conceção, como na sua manipulação e disponibilização ou divulgação. Relativamente à qualidade da geoinformação, destacam-se as normas ISO/TS 19158:2012 - *Geographic information: Quality assurance of data supply* (fornece um enquadramento/estrutura para garantir a qualidade específica da geoinformação e sua disponibilização), ISO 19157:2013 - *Geographic information: data quality* (estabelece os princípios para descrever a qualidade dos dados geográficos) e ISO 19115-1:2014 - *Geographic information - Metadata - Part 1: Fundamentals* (define o esquema necessário para descrever as características da geoinformação e serviços por meio de metadados).

A importância ou peso de variáveis (informação espacial) utilizadas em determinadas modelações (e.g., determinação de probabilidade de ocorrência de incêndios florestais, movimentos de vertente, entre outros) pode ser quantificado recorrendo a determinadas metodologias, como por exemplo os índices *accountability* e *reability* (Blahut *et al.*, 2010). Estes índices revelam-se importantes na identificação das principais variáveis a considerar numa determinada avaliação geográfica, revelando-se assim importantes na seleção da geoinformação a considerar nessa avaliação, o que se pode traduzir na redução da redundância das variáveis a considerar, fator que pode contribuir para a minimização dos custos de aquisição de geoinformação, maior eficiência no desenvolvimento e operacionalização da modelação, entre outros.

Em grande parte dos casos, as referências à geoinformação a considerar numa modelação espacial e os critérios da sua qualidade são ainda escassos, ou mesmo omissos. No contexto português existem algumas referências aos temas a considerar em diversas avaliações espaciais, sobretudo no âmbito da elaboração ou revisão de planos de ordenamento do território (e.g. Reserva Ecológica Nacional – REN), mas as orientações legais por vezes não têm em conta o efeito da escala da geoinformação de *input* para os resultados de todo o processo em análise, ou mesmo erros introduzidos pela própria geoinformação, sejam eles temáticos ou de exatidão espacial ou temporal.

No caso dos erros de exatidão espacial ou de erros temáticos da geoinformação considerada no *input* de uma determinada modelação espacial, por exemplo erros topológicos dos limites dos polígonos (e.g. erros nos limites das divisões administrativas apresentados em diferentes conjuntos de dados), podem culminar em diferentes resultados. Seguindo o exemplo da utilização da geoinformação dos limites administrativos, podem surgir diferentes resultados entre as unidades administrativas (e.g. NUTS ou municípios) para o mesmo tema em avaliação (e.g. UOS), facto explicado simplesmente por erros na geoinformação base que integrou o processo de avaliação desde o início, ou seja, há propagação de erros da geoinformação para os resultados. Neste contexto podem evidenciar-se também as inconsistências espaciais e temáticas entre os conjuntos de dados utilizados.

Outra das discussões sobre os resultados obtidos em análises espaciais são as diferentes tecnologias e interfaces utilizados, vistos como um dos fatores que pode fazer variar a forma como estes são apresentados, onde os utilizadores também têm um papel fundamental, nomeadamente na sua manipulação (Haklay e Nivala, 2010; Kramers, 2008; Medyckyj-Scott, 1993). A utilização de geoinformação em ficheiros de diferentes formatos requer por vezes a sua conversão para a realização das diferentes análises espaciais em diferentes *softwares*, processo que pode conduzir à incerteza na qualidade do *output* dos dados convertidos (Harding, 2013).

Atualmente, estão em desenvolvimento aplicações *web* para a publicação de geoinformação, em grande parte publicação de dados abertos, com o especial enfoque na disponibilização de "dados ligados" (*Linked Open Data* - LOD), permitindo aos utilizadores pesquisas mais profundas e rápidas sobre determinados conteúdos geográficos na *Web*, mas também perceber a relação existente entre os diversos conjuntos de dados (Bauer e Kaltenböck, 2012). Estas iniciativas são vistas como fundamentais para a partilha de geoinformação, no entanto, ainda não são capazes de efetuar avaliações automáticas da qualidade da informação ligada e a sua posterior disponibilização com garantia da ausência de erros, o que pode resultar no enviesamento de resultados quando os utilizadores são menos sensíveis na avaliação da qualidade dessa mesma geoinformação.

1.1.2. Disponibilização da geoinformação

A informação do UOS é cada vez mais abundante, por um lado devido à evolução tecnológica que permite mais recolha de dados em curtos períodos (e.g. satélites) e posteriormente o seu tratamento de forma automatizada ou semi-automatizada, por outro, devido à produção e disponibilização de cartografia por diversas entidades ou instituições, maioritariamente disponibilizada gratuitamente a todos os utilizadores.

Neste contexto, apresentam-se alguns conjuntos de geoinformação atualmente disponíveis a diferentes escalas e respetiva entidade produtora ou proprietária: 1) à escala global: Global Land Cover Characterization (GLCC) – United States Geological Survey (USGS); GlobeLand30 - National Geomatics Center of China; Climate Change Initiative (CCI) Land Cover - European Space Agency (ESA); Global Land Survey (GLS) – Universidade de Maryland e USGS; 2) à escala da Europa: Agência Europeia de Ambiente (AEA); 3) no caso português: Direção-Geral do Território (DGT) e Instituto Geográfico do Exército (IGEOE), atual Centro de Informação Geoespacial do Exército.

Outros dados sobre o UOS (entre outros temas), estão disponíveis *online* na internet, como por exemplo os indicadores estatísticos disponibilizados pelo EUROSTAT ou LUCAS, informação facilmente espacializada com recurso aos SIG.

Face à proliferação de geoinformação foi necessário criar medidas para a sua harmonização, para que todos os dados sejam produzidos e disponibilizados sob condições iguais ou semelhantes. Neste âmbito, uma das iniciativas na Europa foi a criação da Diretiva INSPIRE (Diretiva 2007/02/EC, de 14 de março), que estabeleceu a criação da Infraestrutura Europeia de Informação Geográfica. Esta diretiva foi transposta para a lei portuguesa através do Decreto-Lei n.º 180/2009, publicado a 7 de agosto.

Na atualidade, existem várias iniciativas de partilha de geoinformação (conjuntos de dados geográficos – CDG) através de serviços Web, que se diferenciam em: WMS (*Web Map Service*), WFS (*Web Feature Service*), WMTS (*Web Map Tile Service*), CSW (*Catalogue Services for the Web*), WPS (*Web Processing Services*) e WCS (*Web Coverage Services*).

No caso português, há várias plataformas com disponibilização de CDG através dos serviços *Web* anteriormente referidos, por exemplo, os portais do Sistema Nacional de Informação

Geográfica (SNIG) e do iGEO - Informação Geográfica, onde se disponibiliza também geoinformação do UOS. Contudo, muitos dos WMS disponíveis nas diferentes plataformas apresentam muito pouca informação (ou nem apresentam) sobre a qualidade da geoinformação e sua exatidão nas várias vertentes, problemática explorada também por Blower *et al.* (2015).

Com a crescente disponibilidade de geoinformação de um determinado tema, onde se destaca o UOS, surge a problemática da seleção do conjunto de geoinformação a considerar numa determinada avaliação ou representação espacial de entidades num determinado território. A escolha do conjunto de geoinformação é um exercício complexo, optando-se por vezes pela seleção aleatória, não se contabilizando na maioria dos casos o impacto da integração de determinado conjunto de geoinformação nos resultados obtidos, em detrimento da integração de outro conjunto de geoinformação da mesma temática, mas com diferentes propriedades. Em alguns casos tem-se justificado a seleção e utilização de conjuntos de geoinformação em função da entidade produtora, nomeadamente por existir a garantia implícita de que a geoinformação disponibilizada tem qualidade (validada tematicamente e espacialmente). Neste contexto, apresenta-se por exemplo para o território português a disponibilização da Carta de Ocupação do Solo (COS) ou a CORINE Land Cover (CLC), ambas as cartografias produzidas na DGT, embora a CLC seja disponibilizada pela Agência Europeia de Ambiente (AEA).

A qualidade da geoinformação é um pré-requisito muito importante a considerar na seleção e utilização de CDG (Tveite e Langaas, 1995). Segundo Veregin e Lanter (1995), a avaliação da qualidade da geoinformação (utilizando os SIG) deve seguir uma hierarquia de quatro componentes independentes: identificação da fonte dos erros, deteção e medida/quantificação desses erros, avaliação dos erros de propagação em modelação e, por último, gestão e redução dos erros detetados.

1.1.3. A ERA DO "*BIG DATA*" E DA GEOINFORMAÇÃO VOLUNTÁRIA

O que é "*big data*"? Muitas publicações têm surgido com referência à utilização de "*big data*", sem que para tal se verifique determinadas características para que a informação usada seja considerada "*big data*". Para Wilder-James (2012), "*big data*" são dados que excedem a capacidade de processamento dos sistemas de bases de dados convencionais. Segundo este autor, "*big data*" integra dados muito grandes ou grande volume de dados, aliados a outras duas características, a velocidade e a variedade. Também podem ser vistos como os dados que, contemplando as características anteriores, não se encaixam em determinadas bases de dados devido a restrições derivadas da sua arquitetura, requerendo assim a escolha de formas alternativas de processamento, por forma a proporcionar-se valor a partir dos mesmos. Contudo, quanto maior o volume de dados, maior terá de ser a capacidade de gestão dos mesmos, nomeadamente na verificação da sua qualidade, fator que pode estar comprometido quando esta gestão e a respetiva validação é insuficiente.

A geoinformação dos satélites integra a designada "*big data*", pois compreende as características anteriormente referidas. Neste contexto, também se pode referir que atualmente existe "*big data*" para o UOS, pois são múltiplas as fontes de informação que disponibilizam grandes volumes de geoinformação sobre esta temática, que ao mesmo tempo contempla as características velocidade (aquisição e disponibilização com reduzida resolução temporal) e variedade (múltiplos *datasets* com diferentes propriedades). A variedade deste tipo de geoinformação também pode culminar em diferentes resultados numa modelação espacial quando se utiliza geoinformação obtida por diferentes satélites, porque geralmente apresentam diferentes propriedades (e.g., diferente resolução espectral, espacial, radiométrica ou temporal).

Por outro lado, atualmente existem também iniciativas voluntárias para a recolha e partilha de geoinformação, onde se inclui a geoinformação do UOS. Estas iniciativas tiveram maior afirmação a partir dos anos 2000 (Goodchild, 2007) e são uma versão de *crowd-sourcing* formada por membros do público em geral, que contribuem com informação georreferenciada sobre factos acerca da superfície terrestre ou próxima da mesma (atmosfera ou do subsolo) para *websites*, onde estes são sintetizados dentro de bases de dados (Goodchild e Li, 2012). Estas iniciativas permitem obter de forma voluntária grandes volumes de geoinformação, maioritariamente linhas, pontos e polígonos (uma área), onde se pode incluir atributos como por exemplo o volume (Longley *et al.*, 2011). Porém, aqui coloca-se a questão da qualidade da geoinformação disponibilizada, pois pode variar consoante a precisão dos equipamentos utilizados nessa recolha, o diferente detalhe fornecido pelos voluntários que contribuem para esta recolha, entre outros fatores.

Quanto aos voluntários destas iniciativas, nem todos são profissionais ou qualificados, o que pode fazer variar por exemplo a descrição do elemento geográfico no conjunto de geoinformação recolhida e disponibilizada (e.g., um solo artificializado pode ser apresentado por uns como uma aldeia, vila ou cidade, mas outros podem classifica-lo somente como urbano), a maior ou menor precisão na localização desse elemento, a atribuição de datas diferentes ou pouco precisas na identificação cronológica do evento (e.g. ocorrência de cheias ou inundações, incêndios florestais, etc.), entre outros problemas. Contudo, estas ações voluntárias são vistas na generalidade como um sucesso na aquisição de geoinformação com reduzido custo, mas os utilizadores devem ter consciência das várias deficiências que esta pode apresentar, nomeadamente ao nível da qualidade (Goodchild e Li, 2012).

1.2. USO E OCUPAÇÃO DO SOLO: BREVE ENQUADRAMENTO DAS DINÂMICAS ESPACIAIS E TEMPORAIS A DIFERENTES ESCALAS

Nesta secção apresenta-se uma breve introdução sobre a representação espacial do UOS em diferentes escalas e em diferentes momentos, com análise de algumas alterações de UOS. Inicia-se com uma abordagem desta temática à escala global, depois apresenta-se uma breve introdução sobre o contexto europeu, terminando com uma breve análise à escala nacional (Portugal continental).

1.2.1. À ESCALA GLOBAL

Na atualidade é possível obter geoinformação sobre o UOS a nível global em diferentes momentos, sobretudo geoinformação recolhida pelos satélites. São diversas as fontes com informação de UOS à escala global, mas nem todas partilham da mesma nomenclatura, o que inviabiliza algumas comparações.

Os vários *datasets* com geoinformação de UOS à escala mundial disponíveis também se diferenciam pelas suas diferentes propriedades: resolução espacial, detalhe *versus* generalização temática, entre outras.

Para esta introdução à análise espacial do UOS à macroescala, optou-se pela utilização da geoinformação do projeto ESA CCI Land Cover, pois apresenta geoinformação anual desde 1992 até 2015 (Figura 1.1), permitindo perceber as dinâmicas de UOS num espectro temporal maior, relativamente a outros *datasets* disponíveis.

A partir do *dataset* selecionado para o enquadramento do UOS à escala global apresentado nesta secção, obtiveram-se as áreas por cada tipo de UOS para o primeiro e último ano da série cartográfica disponível e calcularam-se as transições de UOS. Nos resultados obtidos, observaram-se grandes variações de área em determinadas classes de UOS (Figura 1.2), havendo classes com elevada redução de área, mas como aumentam em simultâneo, o balanço final é atenuado, podendo apresentar apenas um ligeiro aumento ou redução de área. Porém, realçam-se algumas classes onde a redução de área foi mais acentuada, por exemplo a classe "Vegetação arbórea, folhosas, perene, fechada para aberta (>15 %)" apresenta elevada redução de área, comparativamente ao que aumentou. Por outro lado, a classe "Áreas urbanas" apresentam essencialmente crescimento aos longo dos 23 anos em análise. Este último tipo de UOS quando estabelecido dificilmente apresenta alteração para outra tipologia de UOS.

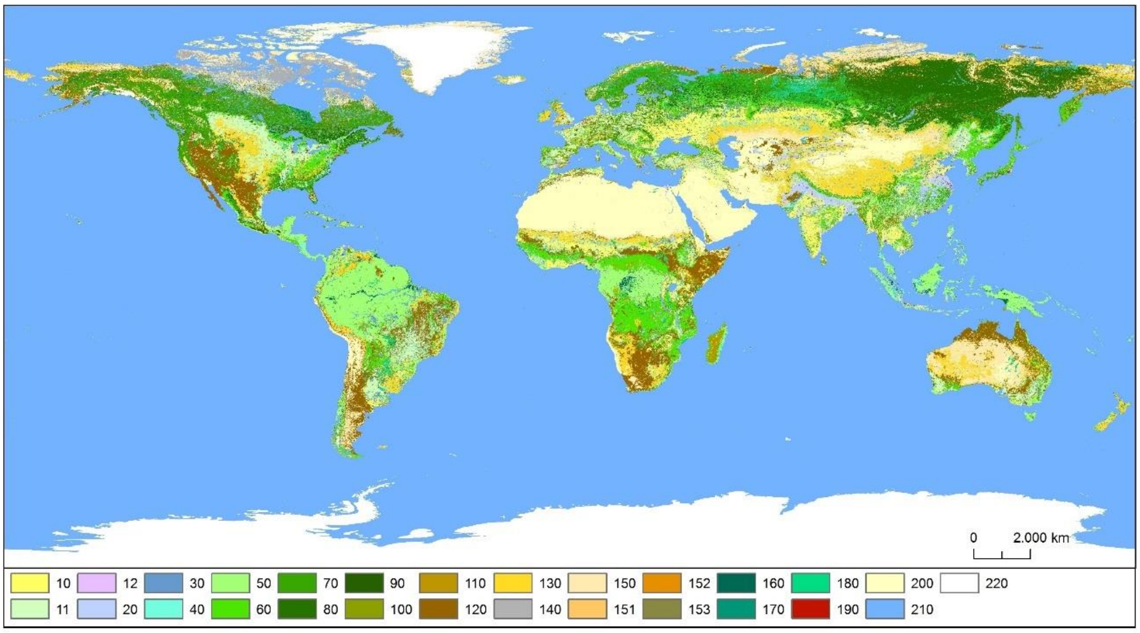

Figura 1.1. Ocupação do solo em 2015 a nível global (adaptado com base na geoinformação do projeto ESA CCI Land Cover).

Legenda: **10** - Área agrícola, sequeiro; **11** - Vegetação herbácea; **12** - Vegetação arbórea ou arbustiva; **20** - Área agrícola, regadio ou em área inundada; **30** - Mosaico de área agrícola (>50%) / vegetação natural (arbórea, arbustiva, herbácea) (<50%); **40** - Mosaico de vegetação natural (arbórea, arbustiva, herbácea) (>50%) / área agrícola (<50%); **50** - Vegetação arbórea, folhosas, perene, fechada para aberta (>15%); **60** - Vegetação arbórea, folhosas e de folha caduca; **70** - Vegetação arbórea, aciculifoliada, perene; **80** - Vegetação arbórea, aciculifoliada e de folha caduca; **90** - Vegetação arbórea, do tipo misto (folhosas e aciculifoliada); **100** - Mosaico de árvores e arbustos (>50%) / vegetação herbácea (<50%); **110** - Mosaico de vegetação herbácea (>50%) / árvores e arbustos (<50%); **120** - Vegetação arbustiva; **121** - Vegetação arbustiva (perene); **122** - Vegetação arbustiva (de folha caduca); **130 –** Pastagens; **140** - Líquenes e musgos; **150** - Vegetação esparsa (arbórea, arbustiva, herbácea) (<15%); **151** - Vegetação arbórea esparsa (<15%); **152** - Vegetação arbustiva esparsa (<15%); **153** - Vegetação herbácea esparsa (<15%); **160** - Vegetação arbórea, em área alagada, água doce e salgada; **170** - Vegetação arbórea, em área alagada, água salina; **180** - Vegetação herbácea e arbustiva, em área alagada, água doce e salgada; **190** - Áreas urbanas; **200** - Solo descoberto; **210** - Corpos de água; **220** - Neves eternas e glaciares.

A esta escala também é possível perceber as dinâmicas de UOS, nomeadamente através das tabelas de transição obtidas pelo cruzamento da geoinformação de UOS de dois anos diferentes. Neste caso, as AUOS observadas a partir da tabela de transição entre 1992 e 2015 (Anexo 1) evidenciam-se: a elevada transição de área da classe "Vegetação arbórea, folhosas, perene, fechada para aberta (>15 %)" para a classe "Mosaico de área agrícola (>50 %) / vegetação natural (arbórea, arbustiva, herbácea) (<50 %)"; a transição da classe "Vegetação esparsa (arbórea, arbustiva, herbácea) (<15 %)" para a classe "Pastagens", ou a transição da classe "Solo descoberto" para as classes "Pastagens" e "Vegetação esparsa (arbórea, arbustiva, herbácea) (<15 %)".

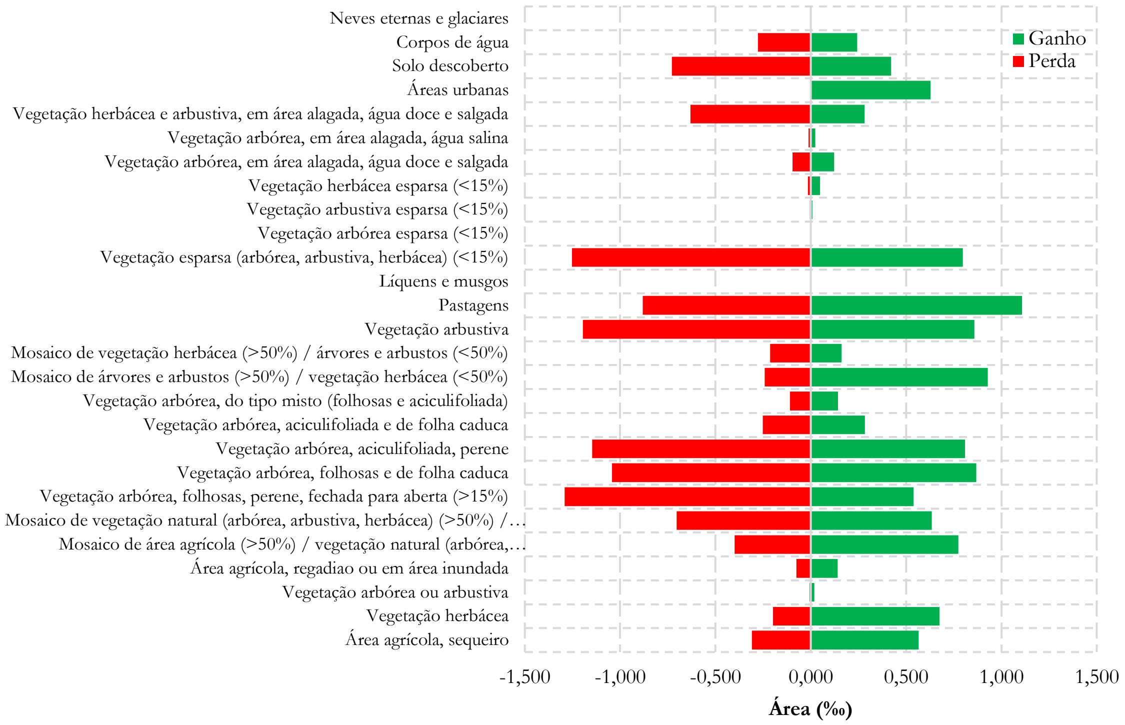

Figura 1.2. Variação da ocupação do solo a nível global entre 1992 e 2015 (resultados obtidos a partir da geoinformação do projeto ESA CCI Land Cover).

1.2.2. À ESCALA EUROPEIA

Alguma geoinformação de UOS também é disponibilizada por vezes à escala de um continente, dando-se os exemplos da Europa (através da AEA) e dos Estados Unidos da América (através da USGS).

À escala europeia, a geoinformação de UOS disponível à escala 1:100 000 é a CORINE Land Cover - CLC. O processo de inventariação desta cartografia teve início em 1985 (para a cartografia do ano 1990), posteriormente atualizado para os anos 2000, 2006, 2012 e 2018. Esta cartografia é produzida individual por cada país, de acordo com as especificações gerais da CLC (EEA, 1995), posteriormente compilada e disponibilizada pela AEA. No entanto, nas várias versões da CLC disponíveis, variou o total de países envolvidos, começando por envolver 26 na versão de 1990, mas com a ocorrência de novas adesões nas versões seguintes, sobretudo países do norte da Europa (Figura 1.3), a versão de 2018 já é o resultado da participação de 38 países (AEA, 2019).

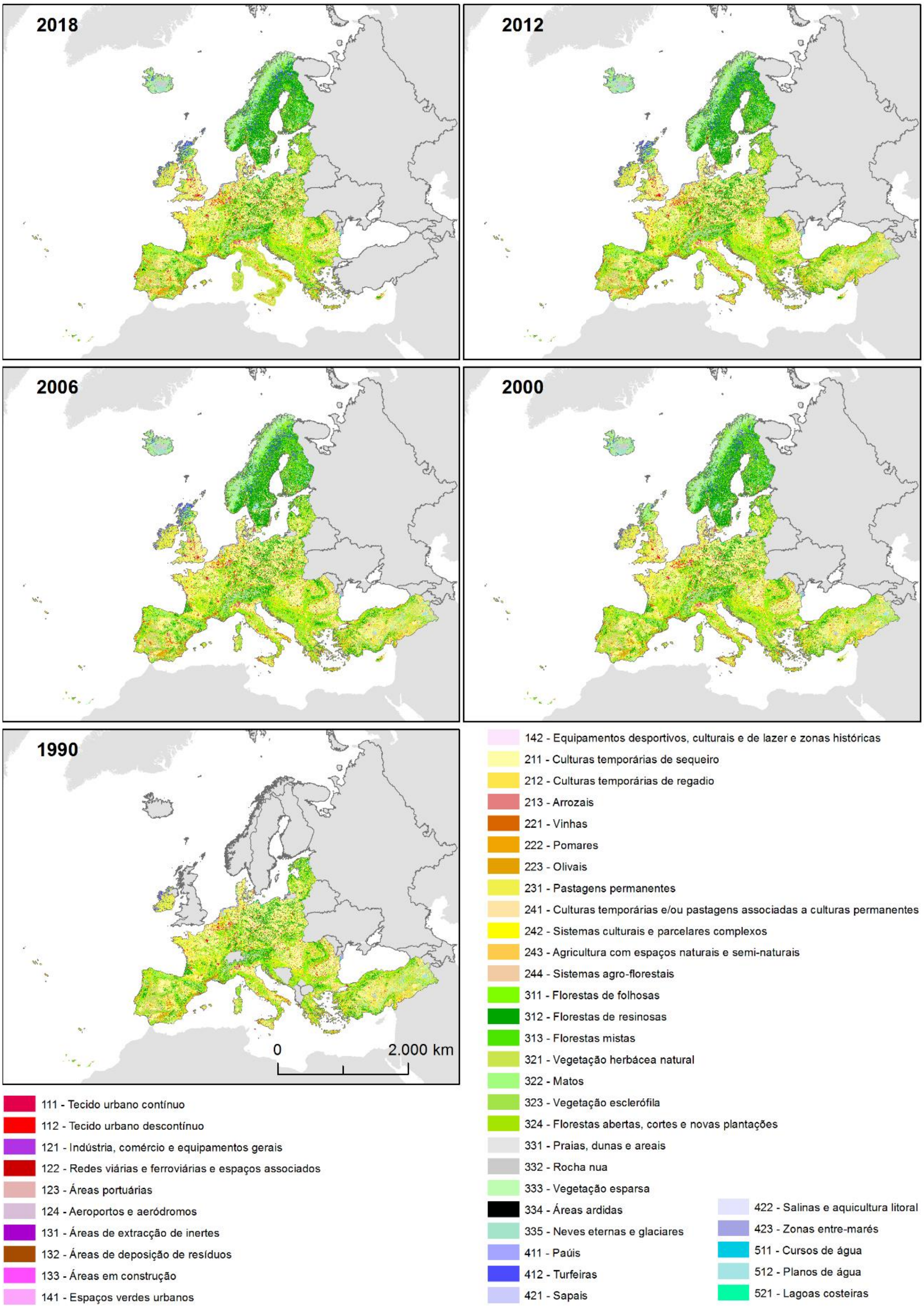

Figura 1.3. Ocupação do solo na Europa. CORINE Land Cover nas suas diferentes versões.

Uma das diferenças da cartografia CLC relativamente a outros *datasets* de UOS é o método de produção, pois envolve fotointerpretação e imagens de satélite, mas também validação com outros inventários (processo variável consoante as equipas dos diferentes países e informação disponível). O principal objetivo da elaboração desta cartografia é apoiar a aplicação das principais áreas prioritárias dos programas de ação em matéria de ambiente da Comunidade Europeia para proteger os ecossistemas, reduzir a perda da biodiversidade, acompanhar os impactes das alterações climáticas, avaliar a evolução da agricultura e suportar a aplicação da Diretiva Europeia do Quadro da Água (EU, 2000), entre outros (AEA, 2019).

Analisando espacialmente o UOS à escala europeia, este é muito diferenciado em latitude, com os países do Norte a destacaram-se pela extensa cobertura florestal, enquanto nos países do Centro/Sul realça-se a ocupação agrícola (sobretudo França e Espanha). Além destes tipos de UOS, também se evidenciam grandes manchas de áreas urbanizadas um pouco por toda a Europa, bem como a demarcação das grandes áreas metropolitanas.

1.2.3. EM PORTUGAL CONTINENTAL

O UOS de Portugal continental também é muito diferenciado espacialmente (Figura 1.4), sobressaindo a maior ocupação florestal no centro do país, as áreas agrícolas no Alentejo e Norte e as áreas urbanizadas no litoral (destaque paras as Áreas Metropolitanas de Lisboa e Porto). Outros tipos de UOS sobressaem em função do relevo de Portugal, por exemplo a ocupação por vinha ao longo do vale do Douro, onde a forma e disposição do vale proporciona um efeito de abrigo, criando condições ótimas para este tipo de UOS.

De acordo com os dados obtidos a partir da CLC 2018, os três tipos de UOS predominantes em Portugal continental são as florestas abertas, vegetação arbustiva e herbácea, as áreas agrícolas heterogéneas e as florestas (Figura 1.5).

As perdas e ganhos de área de cada tipo de UOS que ocorreram em simultâneo no território continental são bastante diferenciadas em termos absolutos; com as florestas a apresentar maior decréscimo de área relativamente ao aumento e, pelo contrário, as florestas abertas, vegetação arbustiva e herbácea a registar maior aumento relativamente à perda (Figura 1.6). As áreas agrícolas temporárias também apresentam maior decréscimo ao longo das várias séries CLC, relativamente ao aumento, mas no ano 2018, a perda foi mais acentuada. Ainda sobre as áreas agrícolas, no caso das áreas heterogéneas, verificou-se valores muito próximos de perdas e ganhos de área, o que de certa forma manteve um equilíbrio do valor total de área nesta classe, mas analisando em pormenor os resultados obtidos, verifica-se que estas variações foram aumentando gradualmente com o passar dos anos, i.e., é um tipo de UOS com alguma dinâmica espacial. Quanto ao tecido urbano, assim como observado nos resultados das análises às escalas macro anteriormente apresentadas, também aqui se verifica aumento, embora este tenha sido mais lento nos anos mais recentes.

Contudo, houve grande variação de área em determinadas classes de UOS entre 1990 e 2018 (de acordo com os dados CLC), destacando-se sobretudo o aumento de área de florestas abertas, vegetação arbustiva e herbácea (aproximadamente 744540 ha), resultando este aumento sobretudo de transições que ocorreram em solos florestais, zonas descobertas e com pouca vegetação, ou áreas agrícolas heterogéneas (Tabela 1.1). Esta transição de UOS justifica em parte a elevada perda de área florestal observada neste território, mas neste caso, as florestas também deram lugar a novas áreas agrícolas (sobretudo as heterogéneas) ou foram devastadas para artificialização do solo (ocupação por tecido urbano, indústria, comércio e transportes).

A análise detalhada do UOS à escala regional para os anos das versões CLC (nível 3) é apresentada no Capítulo 3.

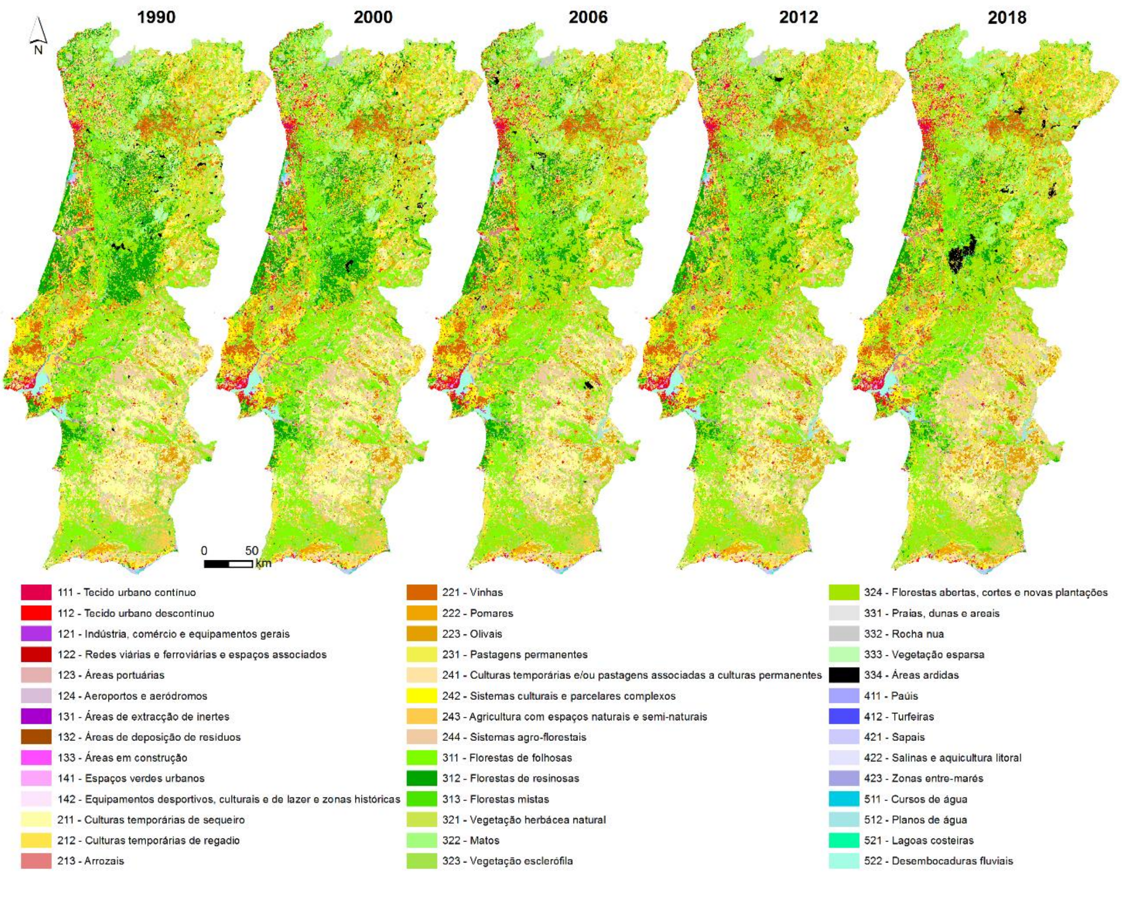

Figura 1.4. Uso e ocupação do solo de Portugal continental (dados da CLC, nível 3).

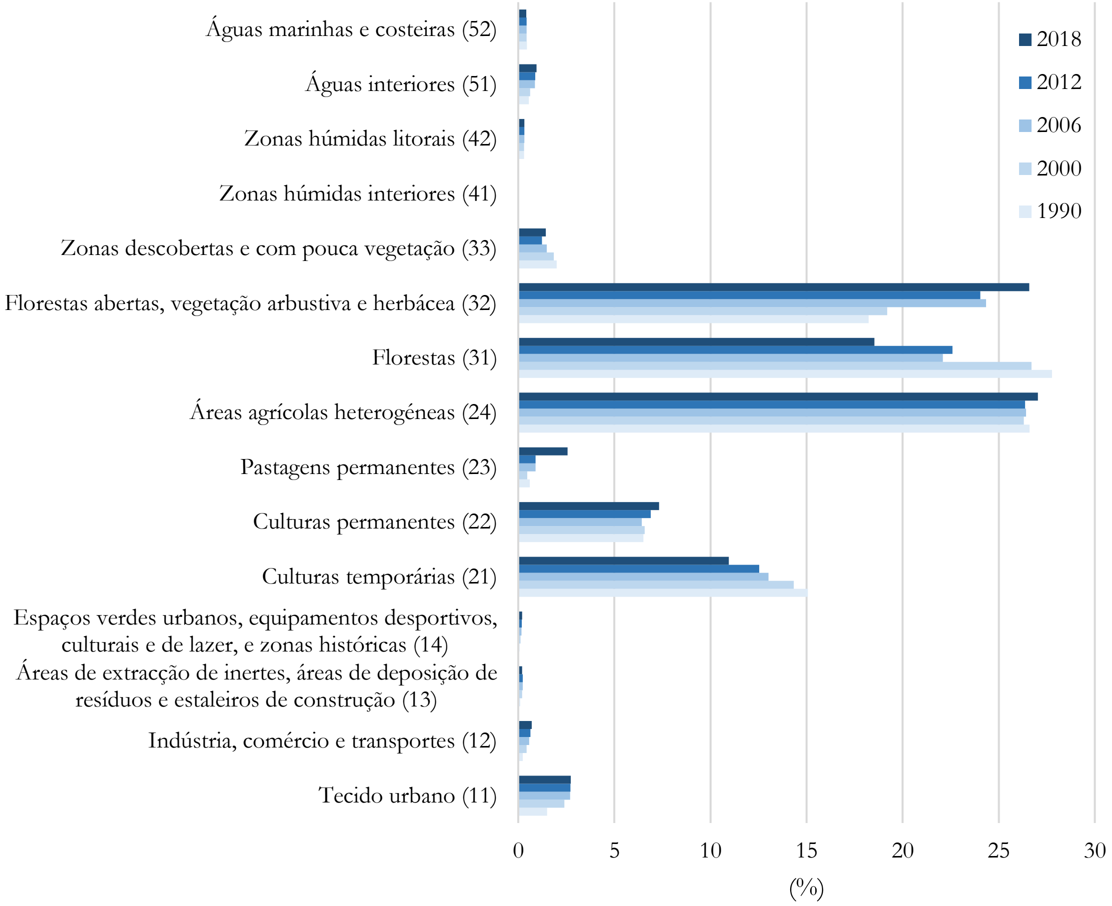

Figura 1.5. Área de Portugal continental por tipo de uso e ocupação do solo (dados da CLC, nível 2).

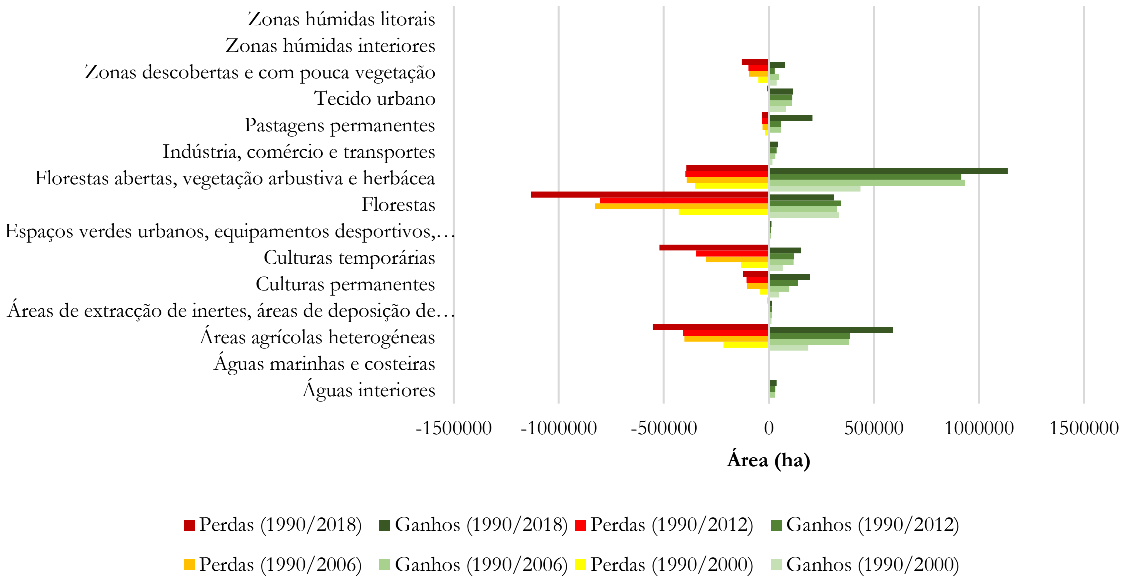

Figura 1.6. Perdas e ganhos de área por tipo de uso e ocupação do solo em Portugal continental (dados da CLC, nível 2).

Tabela 1.1. Área de transição (ha) de uso e ocupação do solo obtida com a geoinformação da CLC (nomenclatura nível 2) entre 1990 e os restantes anos disponíveis (2000, 2006, 2012 e 2018).

	Classe	11 - Tecido urbano	12 - Indústria, comércio e transportes	13 - Áreas de extração de inertes, áreas de deposição de resíduos e estaleiros de	14 - Espaços verdes urbanos, equipamentos desportivos, culturais e de lazer, e zonas	21 - Culturas temporárias	22 - Culturas permanentes	23 - Pastagens permanentes	24 - Áreas agrícolas heterogéneas	31 - Florestas	32 - Florestas abertas, vegetação arbustiva e herbácea	33 - Zonas descobertas e com pouca vegetação	41 - Zonas húmidas interiores	42 - Zonas húmidas litorais	51 - Águas interiores	52 - Águas marinhas e costeiras	Total Geral
		2018															
1990	**11**	127457	2740	56	1218	250	193	32	1214	249	249	82	0	3	8	3	**133754**
	12	1116	19136	121	186	51	4	57	134	160	278	59	0	38	15	13	**21368**
	13	1013	1431	4323	145	13	8	99	237	408	1048	78	0	3	55	27	**8888**
	14	423	233	0	4892	1	3	0	14	55	47	0	0	0	0	0	**5669**
	21	11121	4204	886	1203	822698	95347	136403	147050	17078	97871	108	436	312	8374	11	**1343103**
	22	6150	1723	596	497	18118	456667	3030	58644	6702	24289	383	0	3	2712	2	**579515**
	23	134	84	1	221	18560	447	20640	8851	779	2757	4	129	211	317	1	**53136**
	24	79070	10537	1557	3389	90079	73979	46854	1818714	75022	159845	2429	133	58	9167	13	**2370848**
	31	11323	14936	4923	2945	13553	8852	6669	294015	1340855	736459	30885	2	53	8067	11	**2473548**
	32	5380	6425	5112	2467	12688	16332	14059	76780	203034	1230920	42899	26	299	7606	50	**1624075**
	33	179	487	603	143	474	425	637	3412	7087	114431	49753	0	54	534	218	**178437**
	41	0	0	0	0	8	0	28	17	43	36	0	771	0	8	38	**949**
	42	58	200	17	80	188	11	189	47	2	173	18	155	25485	38	729	**27392**
	51	6	3	0	1	209	127	38	138	127	194	285	8	1	47863	154	**49154**
	52	43	316	0	1	8	1	1	17	2	19	584	2	2152	372	36148	**39666**
	Total Geral	**243472**	**62456**	**18197**	**17389**	**976897**	**652395**	**228735**	**2409283**	**1651603**	**2368616**	**127569**	**1663**	**28673**	**85138**	**37417**	**8909502**
	Ganhos (1990/2018)	116015	43320	13874	12496	154199	195728	208095	590569	310748	1137696	77816	892	3188	37275	1269	
	Perdas (1990/2018)	-6297	-2232	-4565	-777	-520405	-122848	-32496	-552134	-1132693	-393155	-128684	-178	-1907	-1291	-3519	
	Variação (1990/2018)	109719	41088	9308	11720	-366206	72880	175599	38435	-821945	744542	-50868	714	1281	35984	-2249	
		2012															
1990	**11**	129302	2021	116	966	125	67	35	726	194	108	82	0	3	5	3	**133754**
	12	1123	19245	125	186	69	3	36	123	175	216	0	0	38	15	13	**21368**
	13	1026	1415	4625	145	26	9	81	175	396	869	36	0	3	55	27	**8888**
	14	465	233	0	4892	0	3	0	14	54	6	0	0	0	0	0	**5669**
	21	10860	3408	1013	1247	998601	69690	28700	118022	17342	85840	52	474	181	7660	12	**1343103**
	22	5985	1466	663	539	15500	474066	3108	51915	5515	19455	3	0	3	1294	2	**579515**
	23	123	84	2	214	18620	347	22023	7935	655	2491	6	136	186	315	1	**53136**
	24	77322	9309	2187	3148	61547	52638	11950	1963661	58784	122002	314	106	48	7819	13	**2370848**
	31	10186	12702	5678	2521	10716	6248	2008	132532	1669816	606535	7143	2	51	7391	18	**2473548**
	32	5214	5377	5530	2329	11644	10504	11196	71844	247267	1226560	19989	0	291	6285	44	**1624075**
	33	183	389	611	143	418	290	618	2642	12380	78195	81846	0	54	452	215	**178437**
	41	0	0	0	0	29	0	0	16	44	43	0	771	0	8	38	**949**
	42	51	207	18	80	168	10	223	45	2	174	18	154	25475	37	731	**27392**
	51	4	3	1	2	215	70	4	135	150	184	286	8	1	48091	0	**49154**
	52	43	298	0	1	8	1	1	17	2	14	522	2	1614	44	37098	**39666**
	Total Geral	**241886**	**56159**	**20570**	**16413**	**1117685**	**613945**	**79984**	**2349803**	**2012776**	**2142692**	**110298**	**1653**	**27948**	**79473**	**38215**	**8909502**
	Ganhos (1990/2012)	112584	36913	15945	11521	119084	139879	57961	386142	342960	916132	28452	882	2473	31382	1117	
	Perdas (1990/2012)	-4451	-2123	-4263	-777	-344502	-105449	-31113	-407187	-803732	-397514	-96591	-178	-1917	-1063	-2568	
	Variação (1990/2012)	108133	34790	11682	10744	-225418	34430	26848	-21044	-460772	518618	-68139	704	555	30319	-1451	
		2006															
1990	**11**	129358	1979	124	939	116	68	35	716	223	101	83	0	3	5	3	**133754**
	12	1138	19177	152	194	69	3	36	124	184	223	0	0	39	15	13	**21368**
	13	1011	1383	4705	145	26	9	81	175	385	847	36	0	3	55	27	**8888**
	14	465	233	0	4883	0	3	0	23	55	6	0	0	0	0	0	**5669**
	21	10653	2580	1130	963	1043121	31689	28466	117599	12322	86584	82	474	209	7219	14	**1343103**
	22	5931	1251	597	482	15125	476873	2752	51598	4694	19056	9	0	3	1142	2	**579515**
	23	139	81	4	156	17719	103	23291	7935	733	2419	6	136	186	228	1	**53136**
	24	76561	8226	2577	2577	62135	50144	12246	1970061	55844	121981	871	106	48	7458	13	**2370848**
	31	9759	10305	5476	2098	10016	5268	1795	131513	1645111	624073	20802	2	51	7262	18	**2473548**
	32	4913	4230	5495	1769	11583	8918	11274	71441	238441	1232945	26818	0	291	5914	44	**1624075**
	33	183	150	866	142	408	203	563	2675	10461	79545	82597	0	54	375	215	**178437**
	41	0	0	0	0	29	0	0	16	44	43	0	771	0	8	38	**949**
	42	51	192	48	57	168	10	223	45	2	174	18	154	25479	36	734	**27392**
	51	4	3	1	2	238	61	4	137	198	231	285	8	1	47981	0	**49154**
	52	43	298	0	1	8	1	1	17	2	14	522	2	1627	48	37082	**39666**
	Total Geral	**240209**	**50087**	**21175**	**14407**	**1160761**	**573353**	**80768**	**2354074**	**1968698**	**2168241**	**132130**	**1653**	**27993**	**77747**	**38204**	**8909502**
	Ganhos (1990/2006)	110851	30911	16470	9524	117641	96480	57477	384013	323587	935296	49533	882	2514	29766	1122	
	Perdas (1990/2006)	-4396	-2191	-4183	-786	-299982	-102643	-29845	-400787	-828436	-391130	-95840	-178	-1914	-1173	-2584	
	Variação (1990/2006)	106455	28719	12287	8738	-182342	-6162	27632	-16774	-504849	544166	-46306	704	600	28593	-1462	
		2000															
1990	**11**	131302	884	176	630	62	37	1	375	150	72	55	0	1	5	3	**133754**
	12	454	20409	78	141	19	2	0	55	56	91	0	0	35	15	12	**21368**
	13	810	1198	5954	51	5	2	0	91	145	528	41	0	3	55	6	**8888**
	14	47	125	0	5471	0	2	0	18	3	1	0	0	0	0	0	**5669**
	21	8015	1613	773	187	1210836	12048	4983	56988	11311	33952	73	195	138	1986	4	**1343103**
	22	4238	654	653	275	8939	538622	1	19179	2412	4147	178	0	3	214	0	**579515**
	23	82	90	0	93	13600	29	35303	2125	659	1027	9	0	42	78	1	**53136**
	24	59956	5279	2293	1449	28760	26619	564	2155388	36226	51532	352	13	45	2363	9	**2370848**
	31	5817	5205	4201	1197	6873	2856	276	84810	2044837	308268	8560	1	10	632	3	**2473548**
	32	3542	2366	4236	1188	7862	5864	921	24350	271902	1272759	27012	0	254	1816	2	**1624075**
	33	121	112	299	124	169	52	46	830	11236	36616	128469	0	37	175	151	**178437**
	41	0	0	0	0	34	0	0	1	1	0	0	903	0	11	0	**949**
	42	28	89	45	32	152	2	3	9	2	69	10	0	26790	4	158	**27392**
	51	3	0	4	0	194	36	1	91	49	652	279	8	2	47837	0	**49154**
	52	20	210	13	1	7	0	1	5	2	8	159	0	152	0	39088	**39666**
	Total Geral	**214435**	**38236**	**18725**	**10840**	**1277512**	**586172**	**42101**	**2344314**	**2378991**	**1709722**	**165197**	**1119**	**27510**	**55191**	**39439**	**8909502**
	Ganhos (1990/2000)	83133	17827	12771	5369	66676	47550	6798	188926	334154	436963	36728	216	720	7354	351	
	Perdas (1990/2000)	-2451	-959	-2934	-198	-132267	-40893	-17833	-215460	-428711	-351316	-49968	-46	-603	-1318	-579	
	Variação (1990/2000)	80682	16868	9837	5171	-65591	6656	-11035	-26534	-94557	85647	-13240	170	117	6037	-227	

1.3. IMPLICAÇÕES AMBIENTAIS RESULTANTES DAS ALTERAÇÕES DE USO E OCUPAÇÃO DO SOLO

O aumento das AUOS afeta a superfície da Terra ao nível biofísico, biogeoquímico e biogeográfico e ainda a atmosfera (Giri *et al.*, 2013). Estas AUOS também podem constituir um condicionamento ao desenvolvimento dos países, nomeadamente quando estas alterações (e.g. degradação dos solos, destruição de ecossistemas, entre outros) têm repercussões económicas e sociais.

No âmbito das implicações anteriormente referidas, surgiram diversos estudos sobre a quantificação das AUOS, uns de carácter mundial, outros de âmbito nacional ou regional (e.g. Jung *et al.*, 2006; Hansen *et al.*, 2010; DGT, 2013a, 2013b; Giri *et al.*, 2013; Wang *et al.*, 2014). Nestes estudos também se apresentaram diferentes métodos de análise e também diferentes tipos de informação e sua manipulação para a quantificação das AUOS, com destaque para as imagens de satélite (Friedl *et al.*, 2010; Rodriguez-Galiano e Chica-Olmo, 2012).

Uma das grandes preocupações da atualidade relativamente às AUOS é a contribuição para a extinção de muitas espécies, conforme indicado no relatório publicado na Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services em maio de 2019 (IPBES, 2019). Neste relatório são referidos vários tipos de AUOS que vão contribuir para esta extinção de determinadas espécies, como por exemplo o aumento para o dobro das áreas urbanas (desde 1992), o aumento de solos dedicados à agricultura e pecuária, a degradação dos solos, a redução das áreas florestais, entre outros.

Segundo a Agência Europeia de Ambiente (AEA, 2010), o UOS da Europa em 2010 era maioritariamente florestal (cerca de 35 %), seguindo-se as terras aráveis (25 %); as pastagens (17 %); a vegetação seminatural (8 %); as massas de água (3 %); as zonas húmidas (2 %), e as áreas artificializadas (4 %). De acordo com os resultados apresentados por esta agência (AEA, 2010), as tendências de variação de UOS neste território foram muito semelhantes entre 2000-2006, comparativamente ao observado entre 1990-2000, mas já em 2010 se refere a expansão das áreas urbanas à custa das demais categorias de UOS (exceto a floresta e massas de água), constituindo a urbanização e a expansão das redes de transportes os principais fatores de fragmentação dos habitats e de perturbação dos serviços ecossistémicos.

Atendendo às especificações legais adotadas por cada país na avaliação da degradação dos recursos naturais, nomeadamente da água, ainda existe disparidade nos critérios que devem ser considerados nas diversas avaliações de degradação, neste caso perda de qualidade da água (Araújo *et al.*, 2014).

No caso português, as AUOS também foram avaliadas ao nível nacional e regional nas últimas três décadas (e.g., DGT, 2013b, 2013a), verificando-se grandes transições de UOS sobretudo de solos agrícolas para florestas, incultos e artificializados, resultando num forte decréscimo deste tipo de UOS (-5 % em 2010, face ao observado em 1980). Contudo, neste território houve alguns aumentos de área ocupada por florestas (DGT, 2013a), fator favorável ao meio ambiente (contribui para a melhoria da qualidade do ar, retenção de água nos solos, etc.); no entanto, paralelamente a estes aumentos, observou-se também um aumento de ocorrências de incêndios florestais que culminaram na destruição da floresta (Meneses *et al.*, 2018a), destacando-se nestes eventos o aumento da sua intensidade e magnitude, devido à quantidade de material florestal disponível e as condições climáticas favoráveis ao seu desenvolvimento (Shakesby, 2011; Meneses, 2013a).

Os solos têm um papel fundamental na fixação e desenvolvimento da vegetação, mas também por influenciarem os ciclos da água, dos nutrientes e do carbono (AEA, 2010). Destaque para a concentração de matéria orgânica (MO) no solo por ser um importante sumidouro terrestre de carbono, constituindo desta forma uma das principais fontes de mitigação às alterações climáticas (AEA, 2010; Certini *et al.*, 2011). A conversão de determinados tipos de UOS em solos com elevadas concentrações de MO (e.g. solos turfosos, florestais em regime extensivo e alguns prados) constitui uma perda de carbono dos mesmos; associando-se também a estas conversões a diminuição da capacidade de retenção da água e a degradação dos solos (AEA, 2010).

O estudo das AUOS tornou-se atualmente uma preocupação geral, pois é necessário conhecer detalhadamente determinados fenómenos que ocorrem ou ocorreram em diversos territórios, sobretudo para se compreender quais os impactes resultantes ao nível ambiental, económico e social. Paralelamente às investigações realizadas no âmbito desta temática, desenvolveram-se estudos mais específicos para determinar implicações das AUOS na qualidade da água, i.e., perceber a associação entre as AUOS, enquanto causa-efeito, e a redução da qualidade da água, mas também possíveis implicações na sua disponibilidade em quantidade (Erol e Randhir, 2013; Seeboonruang, 2012; Vale, 2002; Warburton *et al.*, 2012).

Segundo Gyawali *et al.* (2013), o UOS e a água (enquanto recurso natural) estão estreitamente ligados. Grande parte das respostas à degradação da qualidade da água dos rios ou lagos estão maioritariamente subjacentes a fatores causais individuais, como por exemplo o *input* de químicos tóxicos (Michael, 2000), perda ou aumento excessivo de nutrientes e/ou a degradação do habitat, entre outros. Neste contexto, ainda são escassas as análises à macroescala, nomeadamente análises mais abrangentes que contemplam todo o meio circundante, porque pode haver outros fatores que estejam a interferir com a qualidade da água (múltiplas fontes de poluição difusa).

De acordo com a Diretiva Europeia do Quadro da Água (EU, 2000), a avaliação da qualidade da água superficial deve contemplar pelo menos mais três fatores padrão na análise: hidrogeomorfológico, químico e ecológico. Contudo, para estes fatores nem sempre é viável a obtenção de dados, emergindo a necessidade de se criar outros indicadores complementares, daí a importância da análise do UOS e respetivas dinâmicas.

A artificialização dos solos em bacias hidrográficas consideradas estratégicas para Portugal continental (produção de energia, mas sobretudo pela disponibilidade de água para consumo humano e suas atividades) aumentou ao longo dos últimos anos (DGT, 2013a, 2013b). Estas intervenções antrópicas têm implicações no território e na qualidade/quantidade de água que chega às albufeiras, nomeadamente no potencial aumento do risco de inundação, devido à impermeabilização do solo, do qual resulta um aumento da escorrência superficial, ou no consequente arrastamento de poluentes das áreas urbanas e agrícolas, acrescido por vezes de descargas ilegais de origem doméstica ou industrial nos cursos de água (Telang, 1990; Pereira *et al.*, 2002; Angeler e Moreno, 2006).

A procura das imediações das albufeiras para a construção de imóveis aumentou ao longo dos últimos anos, dando-se o exemplo das imediações da albufeira de Castelo de Bode (Vale, *et al.*, 2014; Vale, 2002b), por um lado devido ao enquadramento paisagístico que estas áreas encerram, por outro, pela proximidade aos corpos de água, fator que as torna muito procuradas para a realização de atividades lúdicas ou de recreio.

A ocupação urbanística nas áreas envolventes aos corpos de água tem de ser devidamente articulada com a sustentação do meio, de modo a que a expansão urbana tenha o menor impacte na regeneração natural das massas de água. Neste sentido, destaca-se a criação de medidas de planeamento e gestão do território para estes locais, por exemplo, a restrição de determinados tipos de UOS, ou medidas de remediação como por exemplo a melhoria da rede de drenagem de águas residuais domésticas e o tratamento destas águas em estações de tratamento de águas residuais (ETAR). Atualmente alguns empreendimentos constituem uma ameaça à qualidade da água de determinados cursos de água e respetivas albufeiras, sobretudo devido á falta de manutenção ou capacidade de armazenamento de efluentes domésticos nas fossas céticas aí construídas (Costa, 2000).

O aumento de áreas agrícolas com uso intensivo é visto por muitos também como uma ameaça à qualidade das águas superficiais e sub-superficiais, sobretudo devido à elevada quantidade de produtos químicos aplicados nos solos e no tratamento das culturas, por forma a maximizar a produção agrícola (Michael, 2000). A aplicação intensiva de agroquímicos nas áreas agrícolas é uma prática cada vez mais procurada para a intensificação das produções agrícolas, mas a aplicação destes químicos nos solos (geralmente regados intensivamente) acarreta implicações ambientais negativas pelas águas drenadas para os cursos de água a jusante (ou lixiviação dos elementos ou compostos químicos aqui aplicados), causando assim a degradação da qualidade da água (DRAEDM, 1999).

As práticas agrícolas desadequadas podem proporcionar grandes perdas de solo por erosão hídrica, como por exemplo a lavra em sentido perpendicular às curvas de nível (formação de sulcos que favorecem a circulação da água com maior velocidade facilitando a mobilização de solo desagregado), disposição de culturas neste mesmo sentido (e.g. vinhas e pomares), ou a utilização de maquinaria agrícola que cause a desagregação do solo (Meneses, 2011).

A desflorestação assume-se como um verdeiro problema ambiental da atualidade, nomeadamente em Portugal, pelas diversas implicações que tem no meio ambiente, tanto na redução da qualidade do ar e da água, degradação dos solo, como nas implicações económicas resultantes da perda de recursos extraídos diretamente da floresta (SCBD, 2001; Croitoru, 2007; EEA, 2014). Muitas das áreas florestais deram lugar a novas urbanizações ou a infraestruturas, ocupações que interferem no escoamento das águas e na qualidade das mesmas (Buckhouse, 2000; Zipperer *et al.*, 2000).

Em muitas bacias hidrográficas com elevada ocupação de floresta existe ainda o *stress* hídrico induzido pelos incêndios florestais. Estes eventos causam diversos problemas ambientais: poluição do ar, da água e degradação do solo. Destaca-se o facto de deixarem as vertentes sem vegetação, proporcionando o aumento da escorrência superficial e, consequentemente, o aumento da erosão hídrica, podendo causar impactes nas águas a jusante devido ao arrastamento de poluentes resultantes da queima do material florestal que, após os incêndios, ficam depositados na superfície dos solos e são facilmente mobilizados por esta escorrência superficial diretamente para os curso de água (Eriksson *et al.*, 2003; Alexander *et al.*, 2004; Pio *et al.*, 2006; Ferreira *et al.*, 2010a; Smith *et al.*, 2011; Meneses, 2013a).

Os nutrientes incorporados na vegetação (N, P, K, Ca, Mg, Cu, Fe, Mn e Zn) perdem-se durante o incêndio por diversos processos (volatilização durante a combustão, mineralização pela oxidação ou através da convecção das cinzas) (Baker, 1988; Meneses, 2013a), sendo a disponibilidade destes nutrientes influenciada pelo tipo de vegetação e temperatura atingida durante a combustão (Soto e Diaz-Fierros, 1993). Já após o incêndio florestal, os nutrientes contidos na cinza são redistribuídos pelo vento, arrastados pela água de escorrência superficial ou lixiviados (Meneses, 2013a, 2013b). Com a alteração da concentração dos diversos elementos químicos na água, sobretudo devido aos processos anteriormente referidos, a qualidade da água sofre alterações significativas, tornando-se em alguns casos imprópria para consumo humano. Neste contexto, evidencia-se a avaliação das AUOS decorrentes destes eventos, por um lado na identificação do tipo de vegetação presente antes do incêndio, por outro, verificar se é possível a sua regeneração natural, de forma a evitar o potencial *input* dos elementos resultantes dos incêndios nos cursos de água, nomeadamente quando ocorrem as primeiras precipitações capazes de gerar escoamento superficial.

Portugal continental apresenta condições ideais para a ocorrência de incêndios florestais, por um lado há uma época chuvosa que favorece o desenvolvimento da vegetação, por outro tem um período extremamente quente (temperaturas elevadas) e seco (Ferreira *et al.*, 2010), fatores que favorecem a ocorrência destes eventos, agravado por vezes pelo tipo de vegetação presente, como é o caso das resinosas, considerado um material florestal altamente inflamável devido à elevada disponibilidade de resina (Certini *et al.*, 2011).

A gestão da água, de forma a promover desenvolvimento articulado com a garantia da disponibilidade de água, implica o desenvolvimento de modelos de gestão de informação integrados, associados à gestão de cada região hidrográfica de forma a proporcionar a prevenção de situações de *stress* hídrico (quantidade e qualidade). Esta gestão deve estar em articulação com as diferentes estratégias e escalas que integram o modelo global de desenvolvimento de um país (destacando as regiões que compreendem importantes reservas de água), para satisfazer de forma eficiente as necessidades hídricas sentidas pela população e pelos diferentes setores de atividade económica, designadamente em termos de custos, mas ao mesmo tempo, contribuir para a minimização do risco de ocorrência de situações de *stress* hídrico (Vale, 2002, 2009).

A redução da qualidade da água deve-se sobretudo à sua poluição, com maior relevância nas águas superficiais (Pereira *et al.*, 2002; Angeler e Moreno, 2006). Na União Europeia, esta temática tem despertado alguma preocupação, desencadeando a proliferação de medidas para a manutenção da sua qualidade (e.g. EU, 1998). Nas coordenadas da política comunitária da água destaca-se a Diretiva Europeia Quadro da Água n.º 2000/60/CE (EU, 2000), onde se realça a necessidade de proteção das águas de superfície interiores, das águas de transição, das águas costeiras e das águas subterrâneas (Rocha, 2009). Segundo a diretiva 98/83/CE (EU, 1998), com a sua revisão atual, a água destinada ao consumo humano deve ser salubre e limpa, considerada de qualidade quando não contiver microrganismos, parasitas nem quaisquer substâncias em quantidades ou concentrações que constituam um perigo potencial para a saúde humana, devendo para isso respeitar-se os parâmetros microbiológicos e químicos especificados na mesma. Em muitos casos, a degradação da água está associada à descarga de efluentes industriais e urbanos (Telang, 1990; Pham *et al.*, 1999) e também à agricultura intensiva, devido à intensa utilização de agroquímicos (nitratos e produtos fitofarmacêuticos), sendo estes elementos facilmente transportados pela água das regas e da precipitação para os aquíferos e cursos de água (superficiais e subterrâneos), resultando por vezes a sua contaminação (DRAEDM, 1999; Neumann *et al.*, 2002; Pereira *et al.*, 2002; Rozemeijer *et al.*, 2010).

Neste contexto, sobressai a importância da monitorização das AUOS, sobretudo quando estas têm implicações diretas ou indiretas na degradação da qualidade da água (Meneses *et al.*, 2015), destacando-se aqui as áreas que contribuem diretamente para o escoamento que irá alimentar determinadas albufeiras importantes para abastecimento da população. O UOS destas áreas constitui elevada importância na manutenção da qualidade da água., devendo optar-se por tipos de UOS sustentáveis. Assim, nestas bacias hidrográficas deve evitar-se o desenvolvimento de atividades que utilizam intensivamente produtos químicos (e.g. pesticidas ou fertilizantes químicos utilizados em determinadas culturas agrícolas) e que, pelos diferentes meios ou práticas, proporcionam o seu *input* nos cursos de água, reduzindo assim a sua qualidade.

Nas investigações realizadas recentemente na bacia hidrográfica do Rio Zêzere, Meneses *et al.*, (2015) identificaram algumas transições importantes de UOS e a sua correlação positiva com a variação de alguns parâmetros de qualidade da água (PQA), nomeadamente na albufeira de Castelo de Bode. A poluição dos solos e cursos de água a montante das principais albufeiras desta bacia hidrográfica traduziu-se na redução da qualidade da água, sendo em parte o reflexo da excessiva aplicação de químicos nos solos para o aumento de produção agrícola, mas também se deve à disponibilidade de determinados elementos ou compostos, como por exemplo NH_4+ e NO_3^-, formas minerais de azotos em maior quantidade nos solos que, segundo Cordovil (2004), são facilmente mobilização pelas águas drenadas destas áreas, onde as práticas agrícolas desenvolvidas favoreceram o rápido escoamento, reduzindo assim perdas por volatilização e o consequente aumento de concentrações destas formas minerais de azotos nas águas a jusante. No caso desta bacia hidrográfica, considerando apenas a área de drenagem para a albufeira de Castelo de Bode, verificou-se aumento de área de pastagens naturais (embora na totalidade da bacia hidrográfica se tenha observado redução nas últimas duas décadas), estando estas variações de área correlacionadas positivamente com as variações de concentrações de NO_3^-. O aumento de solos ocupados por pastagens naturais neste setor da bacia hidrográfica ocorreu essencialmente devido a transições de solos ocupados inicialmente por florestas de coníferas. As variações de concentrações de NO_2^- e coliformes totais apresentaram as correlações positivas mais elevadas com as variações de área ocupada por olivais, áreas de deposição de resíduos e locais de extração mineral (tipos de UOS com aumento de área neste setor). Já a variação de carência bioquímica de oxigénio a 5 dias (CBO5) está correlacionada positivamente com o aumento de área de solos permanentemente irrigados, áreas em construção, solos urbanizados e ocupados por indústria, enquanto as variações de pH têm elevada correlação positiva com o aumento de solos ocupados por pomares, espaços florestais degradados, cortes e novas plantações. Estes são alguns exemplos de perturbações na qualidade da água derivadas das AUOS.

Com a apresentação de algumas implicações das AUOS e/ou práticas desadequadas do uso do solo para o surgimento ou agravamento de alguns problemas ambientais, evidencia-se a importância da identificação de áreas que constituem um fator de interferência na disponibilidade de água, sobretudo na componente da qualidade. Destaca-se desta forma a importância da avaliação das dinâmicas de UOS, nomeadamente a avaliação espacial e temporal das AUOS. Para estas avaliações é necessário utilizar CDG de UOS e a escolha destes deve ser analisada previamente, pois os diversos conjuntos de geoinformação de UOS disponíveis apresentam, por norma, diferentes propriedades e qualidade (nas suas múltiplas vertentes), fatores que podem culminar em diferentes resultados e, desta forma, proporcionar diferentes conclusões sobre os problemas ambientais em avaliação.

O principal objetivo desta tese é a avaliação das AUOS (a diferentes escalas e temporalmente) utilizando CDG de UOS com diferentes propriedades, de forma a perceber se os resultados obtidos na modelação e análise ambiental apresentada nos seguintes capítulos pode variar consoante a geoinformação considerada. Como são abordados diferentes problemas ambientais, outros objetivos mais específicos são apresentados por cada capítulo de acordo com a problemática em causa dos vários artigos que o compõem.

1.4. ESTRUTURA DO TRABALHO REALIZADO PARA A PRESENTE TESE

Esta tese é constituída essencialmente por artigos científicos, sendo o UOS o tema transversal a todas as investigações apresentadas nos mesmos. Quanto à área de estudo, quatro dos artigos publicados apresentam resultados para Portugal continental, enquanto os restantes apresentam resultados de diferentes investigações realizadas na bacia hidrográfica do Rio Zêzere (Figura 1.7).

A publicação dos vários artigos apresentados ocorreu em diferentes momentos e em diferentes revistas científicas, exceto um publicado num livro de atas de um congresso internacional, pelo que nem sempre foi possível dar continuidade à investigação apresentada em alguns deles, ou fazer referência a estes mesmos artigos noutros artigos também aqui apresentados.

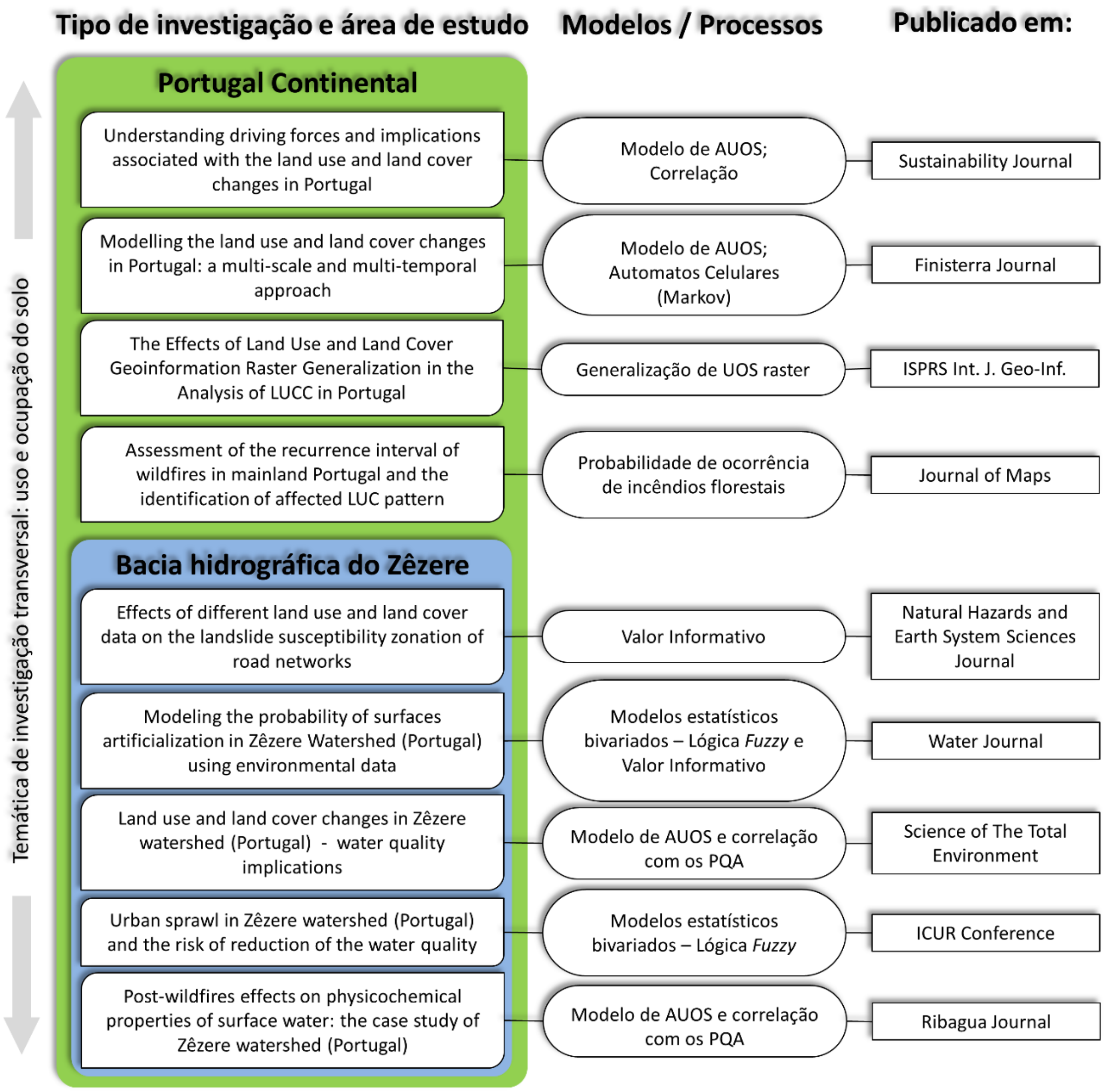

Figura 1.7. Estrutura sintese da investigação: título dos artigos, área de estudo, processos e modelos utilizados, e fonte da publicação.

Para além da temática do UOS transversal a todos os artigos, há relações mais específicas entre as temáticas de alguns artigos, conforme apresentado na Figura 1.8. A divisão dos capítulos tem por base a temática principal dos artigos (referida no título de cada capítulo).

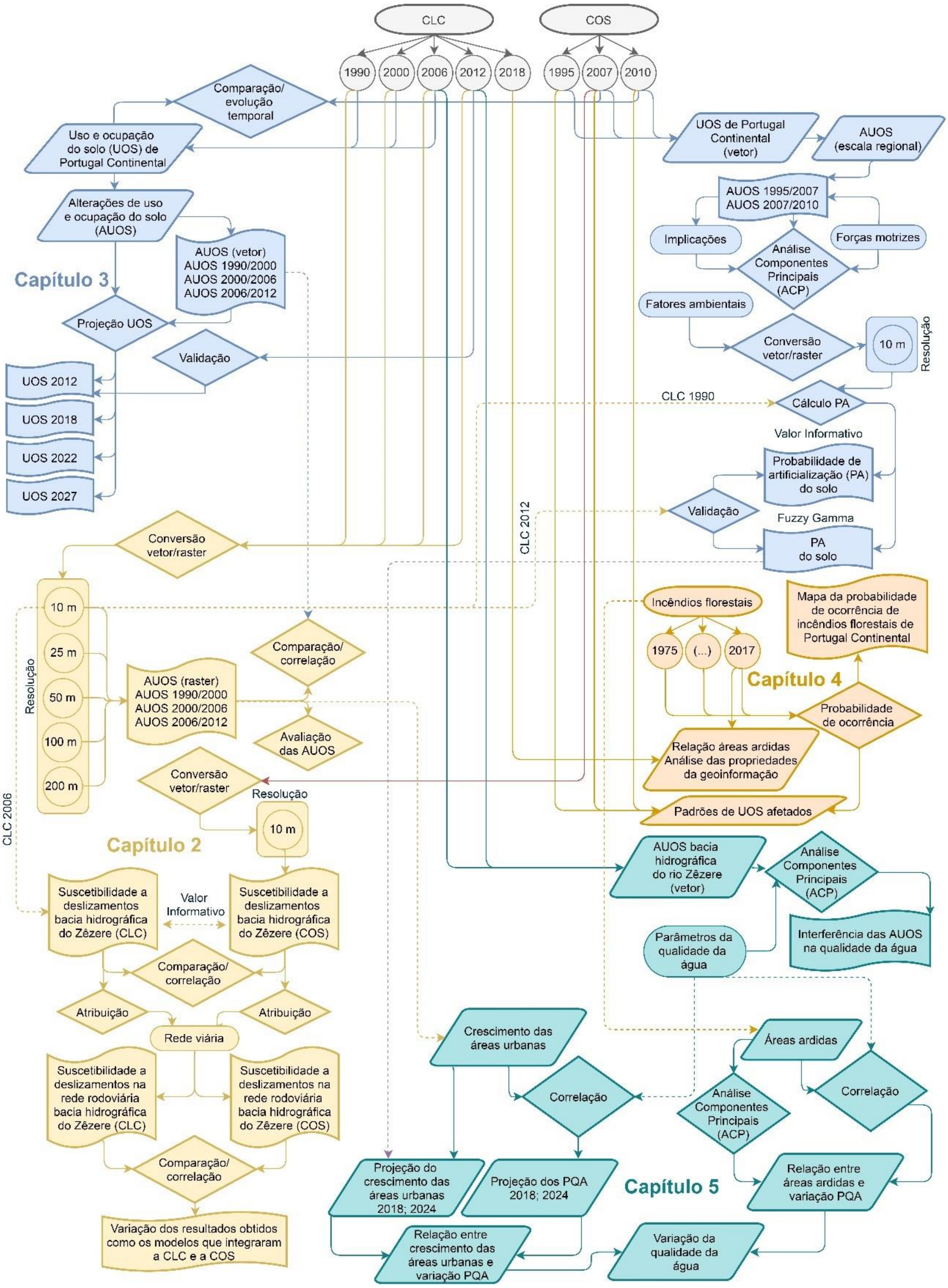

Figura 1.8. Esquema conceptual da interligação da investigação realizada.

Capítulo 2

IMPORTÂNCIA DAS PROPRIEDADES DA GEOINFORMAÇÃO DE USO E OCUPAÇÃO DO SOLO

2.1. INTRODUÇÃO

A geoinformação pode ter diferentes propriedades e ser disponibilizada em duas estruturas (vetor ou *raster*), características já abordadas no capítulo anterior. As propriedades desta geoinformação podem ser muito distintas, desde a escala, a precisão espacial e temática, entre outros. No entanto, as propriedades da geoinformação também se alteram quando se efetuam conversões de vetor para *raster*, ou vice-versa.

Os conjuntos de geoinformação vetorial por vezes têm de ser convertidos em *raster*, pois grande parte das ferramentas de modelação em SIG apenas suporta esta estrutura. Nesta conversão surgem problemas relacionados com a escolha do tamanho da célula (resolução espacial), porque diferentes dimensões conduzem a diferentes interpretações ou diferentes conclusões de um determinado problema analisado espacialmente. Esta foi uma das principais conclusões realçada no artigo que se apresenta na secção 2.2 (Meneses *et al.*, 2018), onde a utilização de *raster* com diferente resolução (nomeadamente com células superiores a 50 m) originou resultados diferenciados sobre as AUOS, sobressaindo as resoluções mais reduzidas (células maiores) com resultados mais distintos, comparativamente aos resultados obtidos com a mesma geoinformação, mas com resolução mais elevada (células inferiores a 50 m). Quanto mais elevada a resolução da geoinformação utilizada no cálculo das AUOS, maior é a correlação com os resultados obtidos a partir da geoinformação vetorial.

Por outro lado, quando se consideram conjuntos de geoinformação com diferentes propriedades, neste caso a COS *versus* CLC para Portugal continental, o comportamento nas diferentes conversões vetor-*raster* também se diferencia, facto que se evidencia na variação de área total de cada classe de UOS nos *outputs* com as diferentes resoluções. Esta variação é explicada sobretudo pelas propriedades da geoinformação vetorial (mais detalhada ou mais generalizada) e pelos diferentes processos que ocorrem nestas conversões à medida que varia o tamanho das células, nomeadamente a ocorrência de processos de fusão ou dilatação que fazem variar a área final de cada classe de UOS. Alguns exemplos destes processos são apresentados no artigo da secção 2.2. Por exemplo, parte dos polígonos classificados como área urbana em áreas rurais (dispersos) na COS vão desaparecer quando a resolução do *raster* é mais reduzida (e.g. superior a 100 m), resultado derivado da reduzida dimensão dos polígonos, enquanto outros polígonos com a mesma classificação vão fundir-se (devido à sua proximidade e dimensão) e parte da informação de polígonos no intermédio de ambos (com outras classificações) vai perder-se, facto verificado por exemplo na classe "Pastagens permanentes". Na CLC, por ser mais generalizada comparativamente à COS, estes processos também ocorrem nestas conversões, mas geralmente em resoluções mais elevadas.

Neste sentido, importa perceber qual o valor de resolução de um *raster* admissível para uma determinada modelação espacial sem comprometer a alteração significativa dos resultados, como é o caso das AUOS, i.e., pretende-se que os resultados derivados de um *raster* sejam iguais ou o mais próximo possível dos resultados obtidos a partir de um vetor, caso contrário, pode-se originar diferentes interpretações e, consecutivamente, diferentes conclusões. Neste sentido, evidencia-se a importância das propriedades da geoinformação para modelação espacial, neste caso as propriedades da geoinformação de UOS na modelação das AUOS e também do risco natural (mais concretamente a ocorrência de deslizamentos).

Contudo, outras questões se formulam quando é necessário realizar a conversão de geoinformação de vetorial para *raster*, pois nem todos os utilizadores usam o mesmo *software* de SIG, mas mesmo que o usem, nem sempre escolhem as mesmas opções nas ferramentas disponíveis. Por exemplo, no ArcGIS 10.6 são múltiplas as especificações disponíveis nos métodos de conversão vetor-*raster*, i.e., a informação atribuída à célula no *output* pode ser: com base na informação do polígono que se sobrepõe ao centro desta célula; com base na área prevalecente de um polígono quando existem vários sobrepostos sobre a mesma célula; com base na área máxima combinada dos polígonos com a mesma informação coincidentes com a mesma célula, entre outros critérios. Nas investigações que se apresentam em seguida esta problemática não foi aprofundada, mas os resultados apresentados são um contributo fundamental para complementar futuras investigações deste âmbito.

O UOS é uma das principais variáveis na avaliação de determinadas tipologias de risco natural, com destaque a avaliação da suscetibilidade ou mesmo do risco da ocorrência de deslizamentos (Beguería *et al.*, 2009; Pisano *et al.*, 2017; Promper *et al.*, 2014). Sobre esta temática têm surgido diversos estudos, muitos deles ligados à utilização de geoinformação obtida pelos satélites (e.g., Guzzetti *et al.*, 2012; Liping *et al.*, 2018; Massetti *et al.*, 2016; Soeters e van Westen, 1996), pois permite mais escolha dentro de uma determinada janela temporal, de acordo com o período do inventário de movimentos de vertente, mas também permite colmatar a inexistência de geoinformação de UOS atualizada em determinados contextos. Por outro lado, também têm surgido estudos evidenciando as AUOS na ocorrência destes eventos (Glade, 2003; Guillard e Zêzere, 2012; Mugagga *et al.*, 2012; Promper *et al.*, 2014), realçando estes a importância da dinâmica do UOS para a ocorrência de deslizamentos, como por exemplo a desflorestação ou ruturas do declive das vertentes para construção de estradas, entre outros.

Quando estão disponíveis vários conjuntos de geoinformação de UOS, como é o caso português, a escolha do conjunto mais adequado para integrar a avaliação da suscetibilidade à ocorrência de deslizamentos com métodos estatísticos também é um exercício complexo. Embora o UOS se apresente como uma das principais variáveis nesta modelação, em muitos estudos desta temática não se justifica a escolha de determinado conjunto de geoinformação de UOS, em detrimento de outro com diferentes propriedades, ou quando se apresenta, os autores justificam a sua escolha com base em critérios fundamentados em alguns pressupostos apresentados no estado da arte destas investigações (e.g. declive, solos, dimensão da área de estudo, entre outros) (Blahut *et al.*, 2010; Castella *et al.*, 2007; Castellanos, 2008; Guzzetti *et al.*, 1999; van Westen *et al.*, 2008; Zêzere *et al.*, 2008; Zêzere *et al.*, 2017).

No artigo que se apresenta na secção 2.3 (Meneses *et al.*, 2019a), discute-se a integração de geoinformação de UOS com diferentes propriedades (COS e CLC) no modelo de determinação do zonamento da suscetibilidade à ocorrência de deslizamentos da rede de estradas da bacia hidrográfica do Rio Zêzere. No anexo 2 apresenta-se o material suplementar deste artigo.

Tal como nos resultados apresentados no artigo da secção 2.2, também se verificou no artigo da secção 2.3 que a utilização de geoinformação mais generalizada de UOS (CLC), face à mais detalhada (COS), resultou na variação dos resultados obtidos na modelação espacial, nomeadamente na variação da suscetibilidade a deslizamentos ao longo das estradas (mais generalizada ao longo dos segmentos das estradas no modelo que utilizou a CLC), enquanto a utilização da geoinformação mais detalhada, permitiu identificar com maior rigor os locais da rede viária onde provavelmente irão ocorrer os próximos deslizamentos. Contudo, os modelos dos quais se obteve os resultados com ambos os conjuntos de geoinformação de UOS apresentam elevado desempenho na determinação da suscetibilidade à ocorrência de deslizamentos.

Relativamente à investigação sobre a suscetibilidade a deslizamentos anteriormente referida, deve ser evidenciado que o UOS é uma variável independente nos modelos apresentados, com grande influência neste tipo de avaliação. Nos dois modelos de suscetibilidade apresentados, todas as variáveis mantiveram-se estáticas, com exceção do UOS, de forma a obter-se resultados diferenciados exclusivamente derivados da variação da geoinformação com diferentes propriedades desta variável. É de referir que o inventário dos deslizamentos utilizado não foi validado na área total de estudo, mas apenas em duas áreas amostra conforme referido no artigo, logo se este inventário for atualizado e a respetiva informação for validada no campo, os resultados apresentados podem variar. Tendo por base estas circunstâncias, seria interessante refazer toda a modelação com um inventário mais completo e perceber se os resultados variam muito relativamente aos apresentados, porque com maior densidade de deslizamentos, podem ser mais distintos e pormenorizados os resultados da suscetibilidade a deslizamentos. Admite-se neste caso que a maior densidade de deslizamentos e a utilização da geoinformação mais detalhada (nomeadamente a COS) podem conduzir à maior diferenciação espacial da suscetibilidade a deslizamentos. Além destes detalhes, outros critérios podem ser testados, por exemplo, no artigo em causa utilizou-se o nível 2 da nomenclatura da COS e CLC, mas será que o comportamento dos modelos varia com a introdução de geoinformação de UOS representado noutros níveis desta nomenclatura (mais agregado ou desagregados, i.e., mais generalizado e detalhado, respetivamente)? Neste sentido, será que esta variável tem a mesma importância na modelação da suscetibilidade a deslizamentos? Ou será que a suscetibilidade a deslizamentos varia muito espacialmente com base nesta agregação ou desagregação? Estes são alguns exemplos de novas possibilidades de investigação que podem ser exploradas futuramente, para as quais os resultados apresentados nesta tese são um contributo fundamental.

2.2. ARTIGO - MENESES, B.M.; REIS, E.; REIS, R.; VALE, M.J. (2018) - THE EFFECTS OF LAND USE AND LAND COVER GEOINFORMATION RASTER GENERALIZATION IN THE ANALYSIS OF LUCC IN PORTUGAL. ISPRS INTERNATIONAL JOURNAL OF GEO-INFORMATION, 7 (10), 390, PP. 1-21.

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The Effects of Land Use and Land Cover Geoinformation Raster Generalization in the Analysis of LUCC in Portugal

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Abstract: Multiple land use and land cover (LUC) datasets are available for the analysis of LUC changes (LUCC) in distinct territories. Sometimes, different LUCC results are produced to characterize these changes for the same territory and the same period. These differences reflect: (1) The different properties of LUC geoinformation (GI) used in the LUCC assessment, and (2) different criteria used for vector-to-raster conversion, namely, those deriving from outputs with different spatial resolutions. In this research, we analyze LUCC in mainland Portugal using two LUC datasets with different properties: Corine Land Cover (CLC 2006 and 2012) and LUC official maps of Portugal (*Carta de Ocupação do Solo*, COS 2007 and 2010) provided by the European Environment Agency (EEA) and the General Directorate for Territorial Development (DGT). Each LUC dataset has undergone vector-to-raster conversion, with different resolutions (10, 25, 50, 100, and 200 m). LUCC were analyzed based on the vector GI of each LUC dataset, and with LUC raster outputs using different resolutions. Initially, it was observed that the areas with different LUC types in two LUC datasets in vector format were not similar—a fact explained by the different properties of this type of GI. When using raster GI to perform the analysis of LUCC, it was observed that at high resolutions, the results are identical to the results obtained when using vector GI, but this ratio decreases with increased cell size. In the analysis of LUCC results obtained with raster LUC GI, the outputs with pixel size greater than 100 m do not follow the same trend of LUCC obtained with high raster resolutions or using LUCC obtained with vector GI. These results point out the importance of the factor form and the area of the polygons, and different effects of amalgamation and dilation in the vector-to-raster conversion process, more evident at low resolutions. These findings are important for future evaluations of LUCC that integrate raster GI and vector/raster conversions, because the different LUC GI resolution in line with accuracy can explain the different results obtained in the evaluation of LUCC. The present work demonstrates this fact, i.e., the effects of vector-to-raster conversions using various resolutions culminated in different results of LUCC.

Keywords: LUC; LUCC; geoinformation properties; raster generalization; spatial analysis

1. LUC: Multiscale Framework, Geoinformation Availability, and Raster Generalization Process

1.1. LUC Changes: An Overview

Global land use and land cover changes (LUCC) research emerged in recent decades when its influence on climate was recognized [1], especially from the mid-1970s, when modification surface albedo and thus surface-atmosphere energy exchanges were verified [2,3].

In the following years, the influence of other processes connected to LUCC were verified, for example, evapotranspiration variation and interference in the water cycle [4], impacts on biotic diversity [5–7], soil degradation [8–11], and other environmental problems. LUCC and land use intensification are major drivers of ecosystem degradation, biodiversity loss, ecosystem service depletion, and landscape change [7,12–15]. Remote sensing, and other data available, in the last decades allow us to obtain a consistent and global picture of the world's landscapes [1].

Land use and land cover (LUC) of Europe comprises a myriad of different landscapes and land uses that reflect topography, as well as climatic and historical changes [16]. In this territory, large LUCC are also verified [17], especially the transitions affecting cropland, forests, and other areas caused by urban growth, and many actions/rules have been implemented to reduce the impacts of LUCC [18].

In Portugal, there are different studies about LUCC [19–24], and these point out large LUCC in recent years, especially with loss of area in forest and agricultural classes and gain of area in urban classes. The LUC datasets used in these studies has different properties (scale, minimum mapping unit, spatial resolution, etc.) and is produced by different entities or individual users, for example, the official Portuguese Land Cover Map (*Carta de Ocupação do Solo*, COS) produced and made available by the General Directorate for Territorial Development (DGT) [25], the Corine Land Cover (CLC) produced by DGT and made available by the European Environment Agency (EEA) and DGT, the LUC classification by satellite images [26,27], and even vectorization on air-photo maps (visual interpretation) made available by different producers or users [28], among others.

Despite some differences in LUCC results from study to study, these can be explained, to a large extent, by the different properties of the geoinformation (GI) used in each study (e.g., References [19,29,30]). These differences can also be related to the processes performed with geographic information system (GIS) tools, in particular the vector-to-raster conversion. Within this vector-to-raster conversion, the properties assigned to data inputs, for instance the cell size or cell assignment method (which, in the polygon-to-raster conversion, is the method used to determine how the value will be assigned to the cell when more than one feature falls within a cell [31], center, maximum area, or maximum combined area, among others), can induce changes in the obtained results.

1.2. LUC Geoinformation

The volume of GI available has greatly increased in recent years. LUC information obtained automatically, semi-automatically, and manually is not an exception, especially because the acquisition is increasingly made in shorter periods (temporal coverage), especially for LUC geoinformation obtained by satellite imagery [32,33]. Furthermore, and more recently, there have been more diverse means of data acquisition, such as unmanned aerial vehicles (UAVs) [34,35]. In addition, there is an increase not only in the amount of available geoinformation, but also in the available data resolution [36–38].

As a result of the increased availability of LUC geoinformation, coming from different sources and collected for different purposes, certain issues have to be considered, and some spatial evaluations have to be made, because data properties vary greatly among the various available datasets. GI properties can be critical in evaluating the quality of the results, because LUC datasets with different properties can lead to different results, which in turn lead to different interpretations and conclusions regarding the LUCC for the same territory under analysis [39].

Several authors have focused also on the quality of GI [40–44], because this can be a decisive issue in obtaining results with high accuracy and quality [45], whether for LUCC or for another type of spatial assessment.

1.3. LUC Geoinformation Generalization

Most analyses of LUCC are produced with GI in raster format, because certain models and tools only support this structure, but questions may arise about the accuracy obtained after vector-to-raster conversion, because real boundaries of elements (lakes, buildings, etc.) are affected or changed in this process. These effects are the result of vector-to-raster conversion, specifically data amalgamation and dilation, emphasizing the importance of cell size [46–48]. In general, it is expected that low resolutions will have negative effects, due to the factors mentioned above.

Shea and McMaster [49] describe the generalization process in 12 processes: Simplification, smoothing, aggregation, amalgamation, merging, collapse, refinement, typification, exaggeration, enhancement, displacement, and classification.

With a GIS, it is possible to use different data models to manage geoinformation [50,51]. At the conceptual level, two models are possible [52]: Object-based ones, where the space is divided into discrete and identifiable entities, each with several properties in terms of geospatial position (e.g., rivers, roads, buildings, etc.); and field-based ones, integrating a continuous mathematical function that for each position of the space returns a value (e.g., temperature, evapotranspiration, insolation, etc.). At the logical level, two structures are available in GIS [52]: Vector (geoinformation represented in lines, points, and polygons), and raster (the space is represented as a regular tessellation of disjoint cells, sometimes called pixels, usually squares, each having an attribute value). The degree of abstraction involved when considering field and object models increases successively from reality to the conceptual model, the logical model, and finally the physical model [51,53].

GIS allows users to produce new coverages by reducing the amount of detail in an existing coverage [45], for example, simplifying LUC polygon boundaries at different scales, but this "generalization" may or may not reduce the number of objects in the coverage [28,54]. The generalization process also occurs when combining polygons with similar characteristics, reducing the number of objects in the coverage.

In raster data, the generalization process usually reduces both the number of objects and the amount of detail [55]. Veregin and McMaster [56] reported that in vector data (e.g., environmental data), the spatial and thematic components can be generalized independently; on the other hand, in a raster generalization this is almost always accomplished by the thematic component alone and the thematic content of maps is changed, thus thematic accuracy and data quality in general can be affected. The confusion matrix [57] is the most common method for assessing the accuracy of thematic data, such as land cover, and is widely used for LUCC assessment (e.g., References [58–62]). The errors that occur in vector-to-raster conversions [63,64] can affect the results; for example, Bettinger et al. [63] observed in the conversion of polygons that forest patch metrics were affected.

In the spatial and temporal LUCC assessment of a given territory, it is important to understand, which impacts may result from the LUCC. Evaluation of LUCC has been done in different territories with different scales of analysis, goals, and methods, but also based on different LUC geoinformation datasets (e.g., References [65–68]). This is a starting point of this work: The vector-to-raster conversion of datasets with different scales is performed and the quality of the LUCC results is evaluated, pointing out the main concerns to have in mind when processing LUC data.

2. Objectives

The first goal of this work is to assess the effects resulting from the GI vector-to-raster conversion, using two LUC datasets with different properties (COS and CLC); the second goal is to evaluate the consistency of LUCC in mainland Portugal obtained by LUC GI referred to above at different resolutions.

As a first approach, the areas of each class in different LUC datasets with different resolutions are reviewed and compared with vector GI; then, using different raster resolutions outputs, the gain and loss of LUCC area are calculated (between raster outputs and also raster verses vector), and the differences between each LUC type (classes), are analyzed. This evaluation is crucial to understand whether the LUCC results vary significantly when LUC datasets with different resolutions are introduced in the model.

3. LUC of Portugal

Mainland Portugal (88,962.5 km^2) is composed of a highly diversified landscape. It integrates large forest areas in the central and northern regions and vast agricultural land in the southern regions (Figure 1), with emphasis on the Alentejo, where the Alqueva Dam (built in 2002) generates a wide water body (the largest artificial reservoir in Western Europe). Artificial surfaces stand out, especially near the coast, and are particularly relevant in the Lisbon and Oporto metropolitan areas.

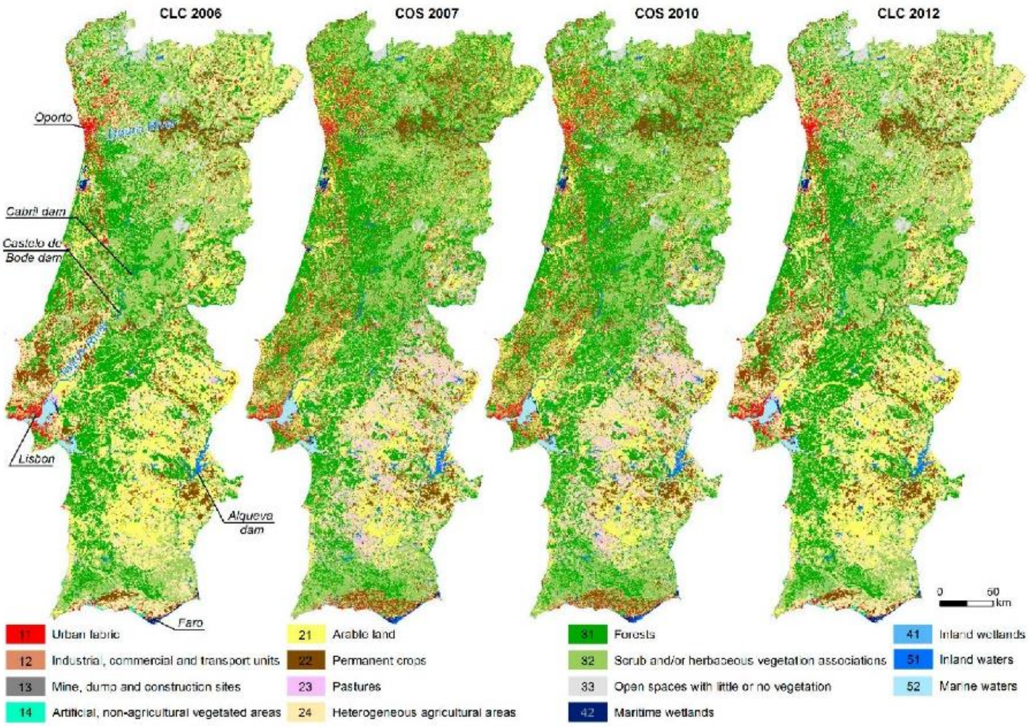

Figure 1. Land use and land cover of mainland Portugal in different years (*Carta de Ocupação do Solo* (COS) and Corine Land Cover (CLC) geoinformation, source: General Directorate for Territorial Development (DGT)).

The assessment of recent decades, this territory has shown significant LUCC, with a large reduction of forest area as a result of yearly forest fires, pinewood nematode infestation [69], and the transition to other types of LUC (e.g., conversion to agricultural land) [22].

Assessing the GI properties is essential to understand the different results on LUCC obtained by different research and to formulate solid conclusions. For example, Figure 1 shows the spatial difference between the soils occupied by a certain type of LUC (e.g., arable land, pastures, heterogeneous agricultural areas, forest) on CLC and COS for the considered years (more details can be found in the attribute tables analysis). Although the cartographic properties are different, the area of arable land in CLC 2006 was higher compared to COS 2007 (about 0.56%), but on the other hand, the forest area was higher in COS 2007 compared to CLC 2006 (approximately 1.66%). These results show the differences that can be obtained in the analysis of LUCC with different LUC GI. Despite the maps being from different years, the period between them is very small, so the results should be similar, with these differences highlighting the importance of understanding certain variations in studying LUCC, particularly those variations, due to the different properties of GI, since there may be different results for the same (or similar) periods, due to a certain set of factors (e.g., scale, spatial resolution, minimum mapping unit, etc.).

Comparing the total areas for LUC classes in different datasets, in general, these show similar variation trends (Figure 2), except class 33 (open spaces with little or no vegetation) with the most significant inverse variations. The line at 45° in the graphs of Figure 2 will then be the reference line, above which the area of land class is decreasing, and below which it is increasing over the selected two years.

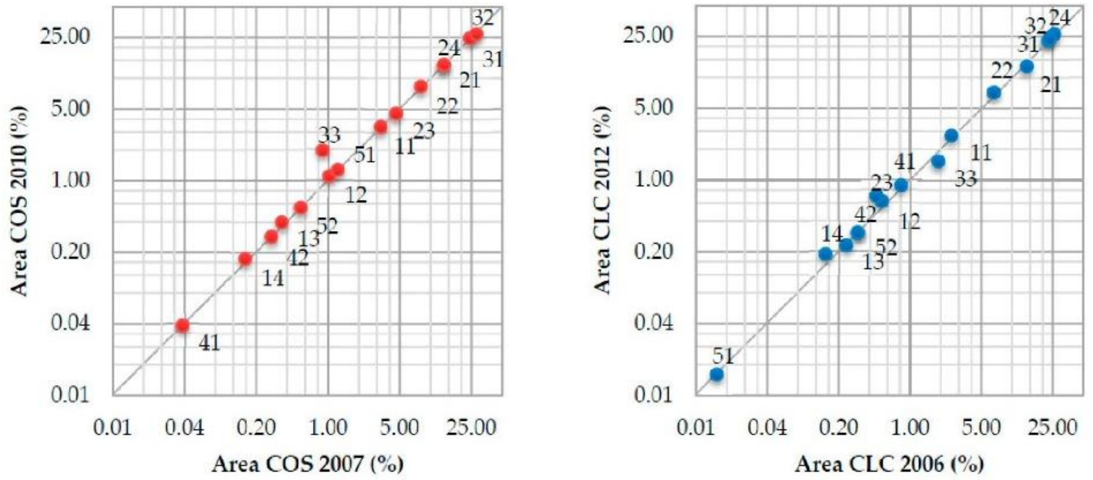

Figure 2. Land use and land cover (LUC, total area) of mainland Portugal in different years, obtained by COS and CLC (vector geoinformation). LUC codes: See legend in Figure 1.

4. Data, Tools, and Methods

4.1. LUC Geoinformation and Multispecifications

The LUC GI used in this research was the COS (2007 and 2010) and the CLC (2006 and 2012). These GI datasets have different properties [25,70], as shown in Table 1. The LUC nomenclature used in these datasets coincides at the first three levels (the same as CLC [71]), allowing the comparison between the two datasets. For this study, only the datasets with greater temporal proximity were selected. Due to the extent of the study area, the second level of the LUC nomenclature used in CLC (which is equal to the second level of the COS nomenclature) was selected for the analysis of LUCC.

Table 1. Characteristics and properties of LUC geoinformation.

Characteristics	Land Cover Maps of Portugal	Corine Land Cover
Acronym	COS	CLC
Scale	1:25,000	1:100,000
Minimum Mapping Unit (MMU)	1 ha	25 ha
Data model	Vector	Vector
Spatial representation	Polygons	Polygons
Minimum distance between lines	20 m	100 m
Base data	Air-photo maps	Satellite images
Spatial resolution	0.5 m	20 m
Nomenclature	Hierarchical (5 levels)	Hierarchical (3 levels)
	225 classes	44 classes
Production method	Visual interpretation	Semi-automated production and visual interpretation
Projected Coordinate System Projection Geographic Coordinate System Datum	ETRS 1989 Portugal TM06 Transverse Mercator GCS ETRS 1989 ETRS 1989	ETRS 1989 Portugal TM06 Transverse Mercator GCS ETRS 1989 ETRS 1989
Data availability (years)	1995 *, 2007, 2010	1990, 2000, 2006, 2012

* Specific nomenclature (hierarchical: two levels with 19 classes maximum at second level) defined to support Kyoto reporting of emissions and carbon sequestration in Portugal [72].

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The administrative boundaries used to perform the study are those of the Official Administrative Map of Portugal (CAOP 2016), in vector structure, provided by DGT. Two LUC datasets (vector GI) were cut and compatibilized by these limits and stored in a geodatabase. The new features resulting from this process have the same total area (88,962.5 km^2) in both maps.

However, there are some differences in the statistics for the feature dataset areas (Table 2). COS features present polygons with a mean area of approximately 11.5 ha in the two years considered; on the contrary, the CLC shows inconsistency between the two years, since features of 2006 and 2012 have polygons with a mean area of 271.6 and 255.2 ha, respectively. The results also differ greatly when considering the number of polygons and the maximum area.

Table 2. Descriptive statistics of LUC GI datasets (vector) after the clip and compatibility by the Official Administrative Map of Portugal (CAOP) 2016 (LUC data obtained by COS and CLC).

	COS		CLC	
	2007	**2010**	**2006**	**2012**
Total polygons	777,262	777,289	32,761	34,867
Minimum area of polygons (ha)	0.01	0.01	0.01	0.01
Maximum area of polygons (ha)	22,439.9	25,799.2	216,104.0	156,114.0
Mean area of polygons (ha)	11.5	11.5	271.6	255.2
Standard Deviation area (ha)	93.5	90.9	2368.3	2136.3

4.2. Tools and LUCC Methodology

The methods used are sequential, with the following steps (Figure 3): (1) introduce the dataset used in research; (2) the vector GI was converted to raster with different resolutions; (3) calculation of the absolute and relative LUCC and analyze the impact of pixel sizes on LUC area; (4) using the vector GI, calculation the compactness coefficient (K_c) and ratio of polygons by total area (PA_{Rt}) for each LUC class; (5) calculation of the correlation coefficients between the indices mentioned above (K_c average and PA_{Rt}) and the area variation between different raster outputs (with different resolution) verses vector GI; (6) using these indices and this variation area, the principal component analysis was used to performed LUC class groupings.

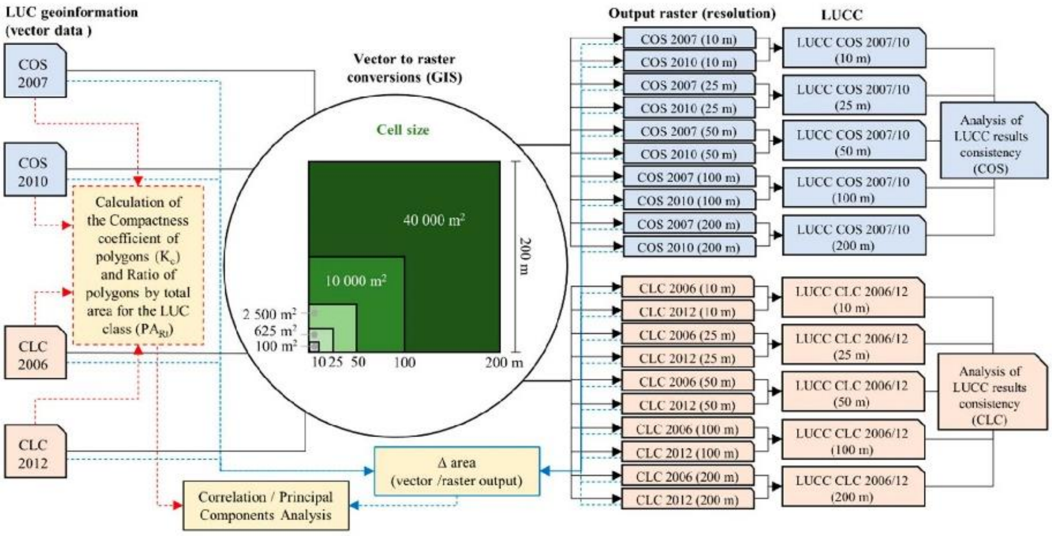

Figure 3. Methodological scheme: LUC GI conversion, LUC outputs, and LUCC.

ArcGIS 10.5 was the selected software to support all GIS processes performed in this research: Vector-to-raster GI conversions, LUCC analysis, and constructing the final LUC maps. In the conversion of LUC polygon features to raster datasets with the software, the cell assignment type selected was "cell center," where the polygon that overlaps the center of the cell yields the attribute to assign to the cell. With the "cell center" option, the priority is specified, and once the cell center falls within only one feature, the attribute of that feature is assigned to the cell [31].

LUCC areas were calculated by subtracting to the LUC final area (t_2) the LUC initial area (t_1) of each LUC dataset ($t_2 - t_1$) [73]. LUC transition tables [74,75] were also prepared for each LUC dataset, to understand in detail LUCC between various LUC types. For this assessment, the LUC GI vector structure (COS and CLC) was converted to raster (using GIS) with different resolutions (10, 25, 50, 100, and 200 m). These results enabled us to quantify the differences between LUCC at different resolution levels (Figure 3) and allowed the comparison of LUCC trends obtained with different LUC datasets.

LUCC results presented in this research were computed with the total area of each LUC vector or raster at different resolutions. Section 5.1 presents the comparison between the total area of mainland Portugal using LUC vector and LUC raster at different resolutions.

The compactness coefficient (K_c) was calculated as a measure to characterize the polygonal form for all GI datasets. This coefficient, mainly used in the calculation of watershed forms [76], is essentially a relationship between the shape of the LUC polygons and that of a circle, and is determined by the following equation:

$$K_c = \frac{0.28 * P}{\sqrt{A}}, \tag{1}$$

where P is the length of the perimeter and A is the area of the polygon.

The ratio of polygons by total area for the LUC class (PA_{Rt}) was also obtained. This ratio provides the variation of polygons by each LUC class and is obtained by the following equation:

$$PA_{Rt} = \frac{\sum_{k=1}^{n} k}{\sum_{A=1}^{n} A}, \tag{2}$$

where K is the number of polygons by LUC class and A is the area of the polygons.

These two variables and absolute and relative LUCC were integrated into the statistical analysis performed in Statistica 7 software. All variables were standardized in Statistica 7.

5. Results and Discussion

5.1. Area of Mainland Portugal at Different Raster Resolutions

Comparing the LUC outputs at different raster resolutions for the total area of mainland Portugal (GI with same coordinate system), it was observed that the total area shows slight variations depending on the selected raster resolution for each LUC dataset (Table 3). Furthermore, the loss or gain of area between the different resolutions is quite variable for each LUC dataset and there is no trend of variation with increasing cell size.

Table 3. Area of mainland Portugal in vector GI and area variation after vector-to-raster conversion.

Luc Dataset	Vector GI	Raster Area Variation Relatively to Vector GI									
		R 10 m		R 25 m		R 50 m		R 100 m		R 200 m	
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2
COS	88,962.5	-2.4^{-05}	-0.022	8.8^{-05}	0.079	-1.0^{-04}	-0.091	2.6^{-04}	0.234	-2.6^{-04}	-0.236
CLC	88,962.5	-5.1^{-06}	-0.005	7.0^{-05}	0.062	2.0^{-04}	0.179	-3.7^{-04}	-0.326	-1.8^{-05}	-0.016

It was also observed that the area loss shown by the COS in raster format with high resolution (10 m) relative to the vector is higher when compared to the area loss observed in the CLC dataset at the same resolution. Different results are obtained when using the 25 m resolution. In this case, both outputs feature a gain in area, especially for the COS dataset. In the output, when using 50 m resolution, the area loss in COS and the gain in CLC are remarkable, but for the 100 m outputs the reverse situation was observed. For the low-resolution raster (200 m), the high area loss in COS relative to CLC stands out.

These differences in area between raster outputs can be related to the cell assignment type selected ("cell center"), where the polygon that overlaps the center of the cell yields the attribute to assign to the cell. According to Bolstad [77], "raster cell assignment may be complicated when representing what we typically think of as discrete boundaries, for example, when the raster value is interpreted as a class code or as a contiguous region ID". According to this author, the type of assignment rules may significantly alter the data layer.

5.2. LUC at Different Raster Resolutions

The areas occupied by the LUC types in the study area vary widely, mostly for the classes with higher percentage of area: "Scrub and/or herbaceous vegetation associations, forests, agricultural areas and arable land heterogeneous". However, a general analysis of the results presented in Table 4 shows a discrepancy between the areas of each LUC class and an inconsistency between some trends of absolute variation between areas for the first and last years of each LUC. For example, the COS presents a trend toward an area reduction in the class "scrub and/or herbaceous vegetation associations", while for the CLC the trend is toward an increase in area.

Table 4. Area of LUC classes (% of mainland Portugal, 88,962.5 km^2) obtained by vector GI and raster outputs with different resolutions for the different years, by each LUC dataset (COS and CLC).

LUC	Vector GI		Raster GI									
			R 10 m		R 25 m		R 50 m		R 100 m		R 200 m	
COS (Years)	**2007**	**2010**	**2007**	**2010**	**2007**	**2010**	**2007**	**2010**	**2007**	**2010**	**2007**	**2010**
11. Urban fabric	3.30	3.34	3.30	3.34	3.30	3.34	3.30	3.34	3.30	3.34	3.31	3.34
12. Industrial, commercial and transport units	1.03	1.11	1.03	1.11	1.03	1.11	1.03	1.10	1.03	1.10	1.03	1.10
13. Mine, dump, and construction sites	0.35	0.39	0.35	0.39	0.35	0.39	0.36	0.39	0.36	0.39	0.35	0.39
14. Artificial, non-agricultural vegetated areas	0.16	0.17	0.16	0.17	0.16	0.17	0.16	0.17	0.16	0.17	0.16	0.17
21. Arable land	13.43	13.25	13.43	13.25	13.43	13.25	13.43	13.25	13.42	13.24	13.43	13.25
22. Permanent crops	8.09	8.28	8.09	8.28	8.09	8.28	8.09	8.28	8.09	8.28	8.09	8.28
23. Pastures	4.64	4.51	4.64	4.51	4.64	4.51	4.64	4.51	4.64	4.51	4.64	4.51
24. Heterogeneous agricultural areas	13.54	13.54	13.54	13.54	13.54	13.54	13.54	13.54	13.54	13.54	13.56	13.56
31. Forests	24.32	24.46	24.32	24.46	24.32	24.46	24.32	24.46	24.32	24.45	24.31	24.45
32. Scrub and/or herbaceous vegetation associations	28.13	26.86	28.13	26.86	28.13	26.86	28.13	26.86	28.14	26.86	28.12	26.84
33. Open spaces with little or no vegetation	0.89	1.97	0.89	1.97	0.89	1.97	0.89	1.97	0.89	1.97	0.89	1.97
41. Inland wetlands	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
42. Maritime wetlands	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
51. Inland waters	1.25	1.27	1.25	1.27	1.25	1.27	1.25	1.27	1.25	1.27	1.25	1.27
52. Marine waters	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.55	0.55
CLC (Years)	**2006**	**2012**	**2006**	**2012**	**2006**	**2012**	**2006**	**2012**	**2006**	**2012**	**2006**	**2012**
11. Urban fabric	2.56	2.70	2.56	2.70	2.56	2.70	2.56	2.70	2.56	2.70	2.56	2.70
12. Industrial, commercial and transport units	0.53	0.62	0.53	0.62	0.53	0.62	0.53	0.62	0.53	0.62	0.53	0.62
13. Mine, dump, and construction sites	0.24	0.23	0.24	0.23	0.24	0.23	0.24	0.23	0.24	0.23	0.24	0.23
14. Artificial, non-agricultural vegetated areas	0.15	0.19	0.15	0.19	0.15	0.19	0.15	0.19	0.15	0.19	0.15	0.19
21. Arable land	13.99	12.74	13.99	12.74	13.99	12.74	13.99	12.74	14.00	12.74	13.99	12.74
22. Permanent crops	6.67	7.08	6.67	7.08	6.67	7.08	6.67	7.08	6.66	7.08	6.66	7.09
23. Pastures	0.47	0.70	0.47	0.70	0.47	0.70	0.47	0.70	0.47	0.70	0.47	0.70
24. Heterogeneous agricultural areas	26.07	26.35	26.07	26.35	26.07	26.35	26.07	26.35	26.07	26.35	26.07	26.35
31. Forests	22.67	22.71	22.67	22.71	22.67	22.71	22.67	22.71	22.66	22.71	22.68	22.72
32. Scrub and/or herbaceous vegetation associations	23.32	23.64	23.32	23.64	23.32	23.64	23.32	23.64	23.32	23.65	23.31	23.64
33. Open spaces with little or no vegetation	1.90	1.52	1.90	1.52	1.90	1.52	1.90	1.52	1.90	1.51	1.90	1.52
41. Inland wetlands	0.82	0.89	0.82	0.89	0.82	0.89	0.82	0.89	0.82	0.89	0.81	0.88
42. Maritime wetlands	0.31	0.30	0.31	0.30	0.31	0.30	0.31	0.30	0.31	0.30	0.31	0.30
51. Inland waters	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
52. Marine waters	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31

The different LUCC observed can be explained by the different properties of each LUC dataset under analysis. Furthermore, there may be changes in LUCC trends as a function of the analysis period, i.e., on the assumption that the COS covers only part of the total period between each CLC (three of the six years), in the total period between the CLC datasets (six years) the tendency of LUCC observed in the first three years, corresponding to the COS period, may be different than what occurred in the last three years of the period. The same thing could happen for the results of the CLC if we consider the same period between each COS (three years), i.e., the area of a LUC type can increase or reduce, and this result is not exactly equal to what is observed for the LUCC obtained with the COS.

In the process of vector to raster GI conversion, the bigger the cell size, the greater the generalization of the represented GI [63,78], which is widely acknowledged in this type of GIS conversion. Figure 4 represents a LUC extract for each LUC dataset, where this generalization is shown. This extract was selected since it allows us to show concrete examples of generalization in different raster outputs. Classes with bigger area, e.g., water bodies, but with great variation in the shape of polygons result in different aggregations in the vector-to-raster conversion (e.g., the Zêzere River loses representativeness at low resolution), but on the other hand, some effects of generalization in polygons with reduced area, e.g., in the class urban fabric of COS, can also be noted. Major changes are visible for the sample with lower resolution (larger cell size), as well as the amalgamation and dilation of LUC GI (e.g., scrub and/or herbaceous vegetation associations and heterogeneous agricultural areas). Other LUC types, such as water course (Zêzere River) or heterogeneous agricultural areas, are not represented in the low-resolution raster (greater than 100 m cells), because of their reduced area in determined segments and the relatively small distance between lines (riverbanks in the case of the Zêzere River). The errors of area (polygon) conversions and the effects of polygon size and shape and raster cell size are described in some studies [79–81].

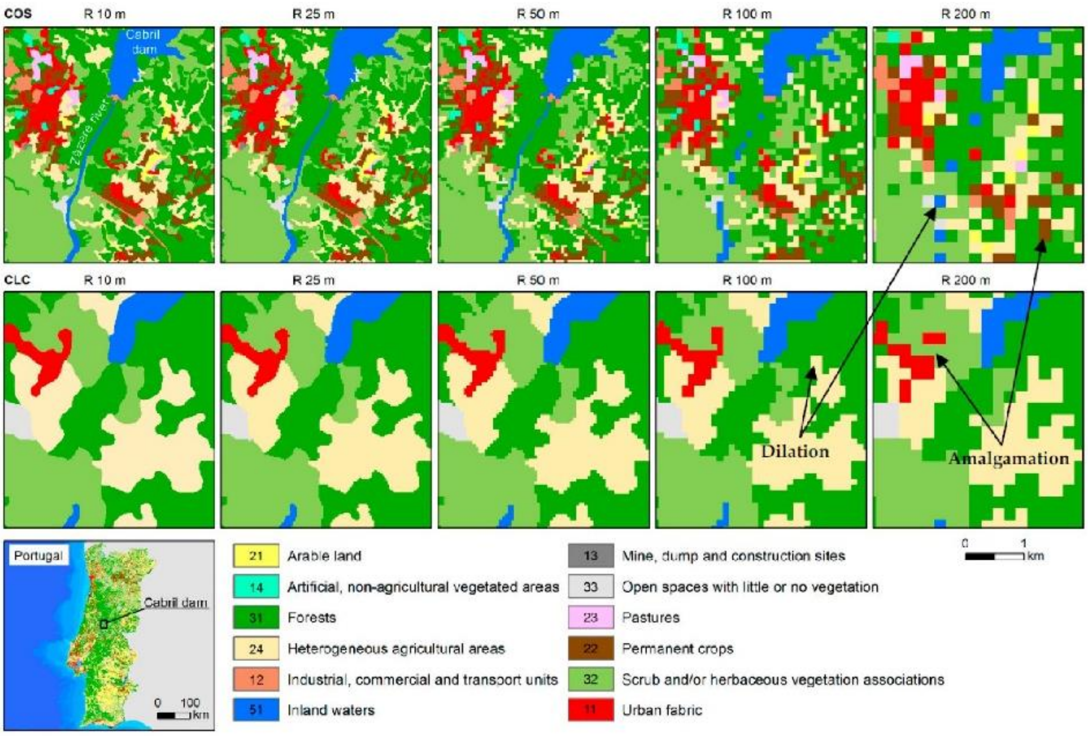

Figure 4. LUC extracts with different resolutions (COS 2010 and CLC 2012) in the central region of Portugal (downstream of Cabril Dam).

Comparing the COS and CLC outputs for different resolutions, the COS outputs are more spatially complex (see example in Figure 4), mainly due to the greater detail of the GI in this LUC dataset (minimum mapping unit (MMU) 1 ha). COS allows the spatial representation of more LUC classes compared to CLC (because of the inherent scale of the GI). This is one of the characteristics that also contributed to the greater dispersion of LUC in the samples of COS represented in Figure 4. The processes of amalgamation and dilation can be more important, due to the form and area of each polygon of LUC, and the distance (proximity or remoteness) between polygons with the same attribute.

The CLC vector dataset, due to its inherent characteristics/specifications, has greater generalization of LUC than the COS vector dataset. According to Yang et al. [82], generalization of the LUC GI cannot dispense with the aggregation and amalgamation operations of the patch polygons.

Relative and absolute changes between the total area for each LUC type in the different outputs for different raster resolutions (per year) vary widely (Figure 5), being more significant as cell size increases.

Some LUC types present bigger areal difference in relation to the area measured in the vector GI when the cell size increases (Table 5). However, these differences are not common between the LUC datasets considered in the analysis, or even between the outputs with different resolutions. For example, in the case of COS, there is an increase of 0.01% in urban area in the 200 m raster output, while in the class "Industrial, commercial and transport units", there is a loss of area, but the same cannot be observed in the outputs of the CLC.

Table 5. Main variation areas (gain ≥0.01% and loss ≤−0.01% of mainland Portugal) of the LUC raster (COS 2007 and 2010; CLC 2006 and 2012) relative to LUC areas in vector GI.

LUC	COS (R 100 m)		COS (R 200 m)		CLC (R 200 m)	
	2007	2010	2007	2010	2006	2012
11. Urban fabric	0.00	0.00	0.01	0.00	0.00	0.00
12. Industrial, commercial and transport units	0.00	0.00	−0.01	0.00	0.00	0.00
21. Arable land	−0.01	−0.01	0.00	0.00	0.00	0.00
22. Permanent crops	0.00	0.00	0.00	0.00	0.00	0.01
24. Heterogeneous agricultural areas	0.00	0.00	0.02	0.02	0.00	0.00
31. Forests	−0.01	0.00	−0.01	0.00	0.01	0.01
32. Scrub and/or herbaceous vegetation associations	0.01	0.01	−0.01	−0.02	−0.01	−0.01

In the outputs at low resolution (pixel size greater than 100 m), there were LUC classes that showed breaks in the variation trend compared to those observed in outputs with higher resolution (10, 25, or even 50 m). This reversal of area variation for each LUC type (Figure 5), among the different resolutions, is not equal or similar in the different years for the same LUC dataset. This variation can be explained by LUCC that occurred in the period between each LUC data acquisition year, but also because of the different effects that occur in the vector-to-raster conversion process.

LUC classes with reduced area (for example, inland and maritime wetlands, and inland and marine waters) show the highest relative changes for different raster resolutions, and they are more significant at low resolution (200 m).

5.3. LUCC at Different Raster Resolution Levels

LUCC in mainland Portugal are very distinct between the different LUC types. In absolute terms, the most important LUCC show high loss and gain of area in the classes "forest and scrub and/or herbaceous vegetation associations" of the COS results (2007 to 2010), and for the same classes in the results obtained by the CLC (2006 to 2012), but in this last dataset the "heterogeneous agricultural areas" also show relevant area changes (Table 6). These results are consistent with LUCC presented by other research [22,39,72].

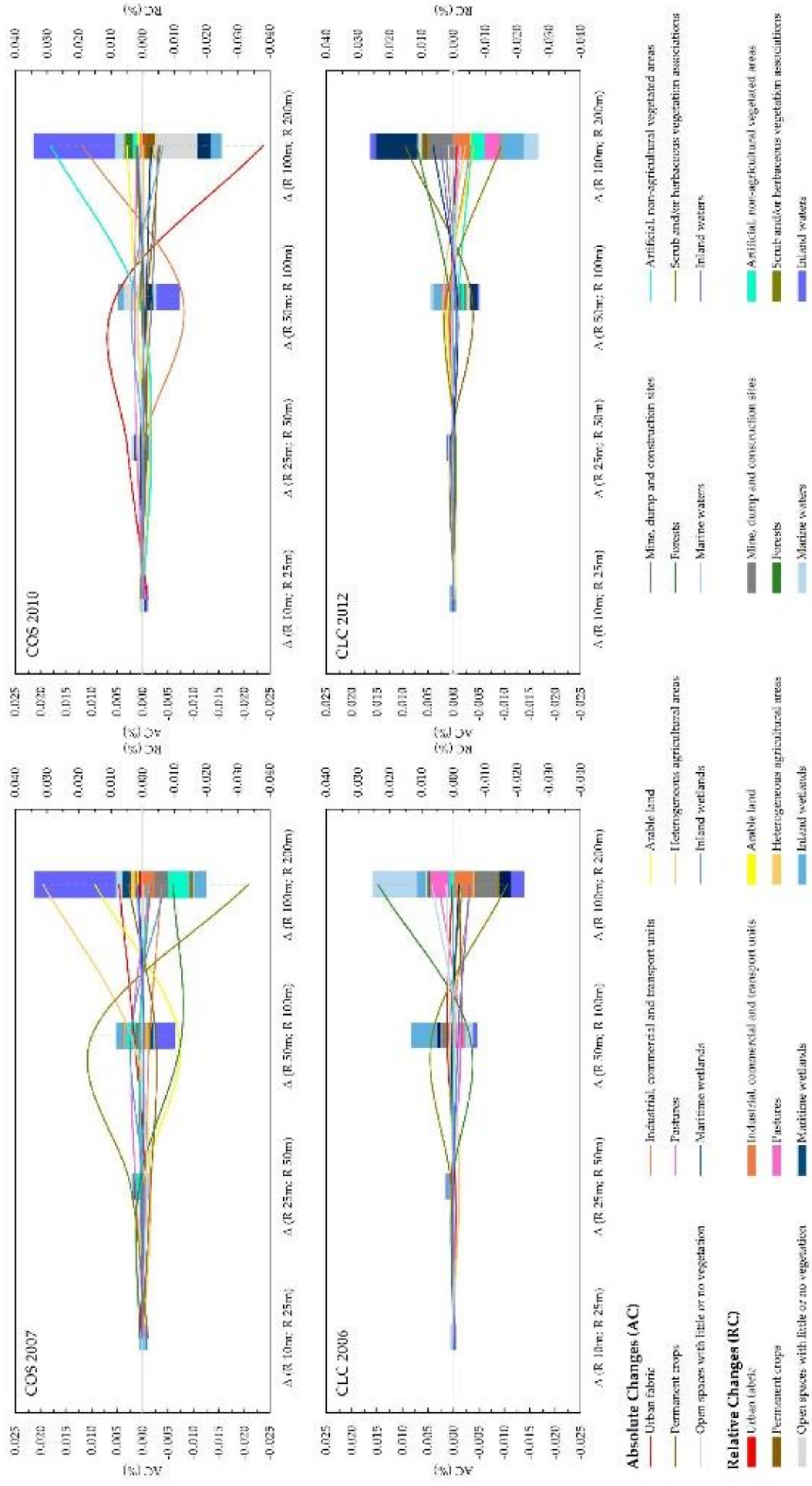

Figure 5. Absolute and relative change variation (% area) between LUC geoinformation with different resolutions (R, raster resolution in meters).

Table 6. Gain and loss area (% of mainland Portugal) by LUC type (absolute changes), obtained for different raster resolutions outputs. Values in bold represent above average gain and loss areas for each dataset (COS and CLC).

	LUC	Vector Data		R 10 m		R 25 m		R 50 m		R 100 m		R 200 m	
		Loss	Gain	Loss	Gain	Loss	Gain	Loss	Gain	Loss	Gain	Loss	Gain
COS 2007 to 2010	11. Urban fabric	−0.0021	0.0386	−0.0021	0.0386	−0.0021	0.0385	−0.0021	0.0388	−0.0021	0.0385	−0.0023	0.0371
	12. Industrial, commercial and transport units	−0.0019	0.0753	−0.0019	0.0752	−0.0019	0.0753	−0.0019	0.0752	−0.0020	0.0758	−0.0020	0.0762
	13. Mine, dump and construction sites	−0.0653	0.1017	−0.0653	0.1017	−0.0652	0.1016	−0.0654	0.1018	−0.0662	0.1013	−0.0652	0.1003
	14. Artificial, non-agricultural vegetated areas	−0.0008	0.0164	−0.0008	0.0164	−0.0008	0.0163	−0.0008	0.0164	−0.0008	0.0167	−0.0007	0.0153
	21. Arable land	**−0.4373**	0.2549	**−0.4373**	0.2549	**−0.4372**	0.2550	**−0.4373**	0.2550	**−0.4381**	0.2550	**−0.4370**	0.2563
	22. Permanent crops	−0.1733	**0.3631**	−0.1733	**0.3631**	−0.1733	**0.3632**	−0.1731	**0.3631**	−0.1730	**0.3652**	−0.1742	**0.3635**
	23. Pastures	−0.2227	0.0910	−0.2226	0.0910	−0.2226	0.0910	−0.2228	0.0909	−0.2233	0.0909	−0.2205	0.0907
	24. Heterogeneous agricultural areas	−0.1677	0.1668	−0.1677	0.1667	−0.1677	0.1668	−0.1678	0.1667	−0.1684	0.1661	−0.1699	0.1661
	31. Forests	**−1.5494**	**1.6818**	**−1.5493**	**1.6817**	**−1.5496**	**1.6816**	**−1.5496**	**1.6810**	**−1.5458**	**1.6830**	**−1.5485**	**1.6887**
	32. Scrub and/or herbaceous vegetation associations	**−2.6999**	**1.4263**	**−2.6999**	**1.4263**	**−2.6997**	**1.4262**	**−2.6993**	**1.4264**	**−2.7030**	**1.4253**	**−2.7074**	**1.4268**
	33. Open spaces with little or no vegetation	−0.0876	**1.1690**	−0.0875	**1.1690**	−0.0875	**1.1692**	−0.0875	**1.1692**	−0.0874	**1.1694**	−0.0881	**1.1715**
	41. Inland wetlands	0.0000	0.0001	0.0000	0.0001	0.0000	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000
	42. Maritime wetlands	−0.0001	0.0001	−0.0001	0.0001	−0.0002	0.0001	−0.0002	0.0001	−0.0001	0.0001	−0.0001	0.0001
	51. Inland waters	−0.0005	0.0237	−0.0005	0.0237	−0.0005	0.0237	−0.0005	0.0237	−0.0006	0.0236	−0.0004	0.0238
	52. Marine waters	−0.0001	0.0000	−0.0001	0.0000	−0.0001	0.0000	−0.0001	0.0000	0.0000	0.0000	−0.0001	0.0000
CLC 2006 to 2012	11. Urban fabric	−0.0958	0.2387	−0.0958	0.2387	−0.0959	0.2387	−0.0955	0.2387	−0.0959	0.2384	−0.0971	0.2387
	12. Industrial, commercial and transport units	−0.0401	0.1303	−0.0401	0.1303	−0.0401	0.1303	−0.0401	0.1301	−0.0400	0.1306	−0.0401	0.1310
	13. Mine, dump and construction sites	−0.0867	0.0796	−0.0867	0.0796	−0.0867	0.0796	−0.0868	0.0797	−0.0873	0.0800	−0.0860	0.0794
	14. Artificial, non-agricultural vegetated areas	−0.0046	0.0451	−0.0046	0.0451	−0.0046	0.0451	−0.0046	0.0452	−0.0046	0.0447	−0.0044	0.0459
	21. Arable land	**−1.9297**	0.6756	**−1.9297**	0.6755	**−1.9298**	0.6755	**−1.9299**	0.6753	**−1.9302**	0.6759	**−1.9267**	0.6700
	22. Permanent crops	−0.5920	**1.0107**	−0.5920	**1.0107**	−0.5920	**1.0108**	−0.5919	**1.0108**	−0.5924	**1.0092**	−0.5885	**1.0159**
	23. Pastures	−0.1106	0.3395	−0.1106	0.3395	−0.1107	0.3396	−0.1106	0.3396	−0.1099	0.3395	−0.1110	0.3387
	24. Heterogeneous agricultural areas	**−1.9740**	**2.2551**	**−1.9739**	**2.2550**	**−1.9740**	**2.2549**	**−1.9737**	**2.2557**	**−1.9723**	**2.2564**	**−1.9724**	**2.2552**
	31. Forests	**−2.9602**	**3.0069**	**−2.9602**	**3.0069**	**−2.9602**	**3.0069**	**−2.9604**	**3.0066**	**−2.9593**	**3.0093**	**−2.9672**	**3.0095**
	32. Scrub and/or herbaceous vegetation associations	**−3.6996**	**4.0261**	**−3.6996**	**4.0262**	**−3.6994**	**4.0263**	**−3.6996**	**4.0256**	**−3.7032**	**4.0263**	**−3.7003**	**4.0247**
	33. Open spaces with little or no vegetation	−0.6575	0.2772	−0.6575	0.2772	−0.6575	0.2772	−0.6574	0.2773	−0.6588	0.2776	−0.6571	0.2770
	41. Inland wetlands	−0.0090	0.0774	−0.0090	0.0774	−0.0090	0.0775	−0.0090	0.0774	−0.0088	0.0772	−0.0091	0.0771
	42. Maritime wetlands	−0.0089	0.0057	−0.0089	0.0057	−0.0090	0.0057	−0.0089	0.0057	−0.0090	0.0057	−0.0093	0.0057
	51. Inland waters	−0.0020	0.0020	−0.0020	0.0020	−0.0020	0.0020	−0.0020	0.0020	−0.0020	0.0019	−0.0022	0.0019
	52. Marine waters	−0.0016	0.0023	−0.0016	0.0023	−0.0016	0.0023	−0.0016	0.0023	−0.0015	0.0023	−0.0019	0.0025

However, the LUCC results are not coherent among themselves when using the different resolutions of the two raster datasets considered in this research. The area loss or gain between different raster resolutions is very variable for different LUC classes. For example, in the COS LUCC results, the area loss in the forest class using the 25 m resolution, relative to vector GI, presents a slight increase, but when using 100 m raster resolution there is a slight reduction of area. The results for the forest class obtained with low resolution (200 m) again show an area loss. The reverse situation is observed for higher resolutions, where there is a reduction in area increase when cell size increases, but this situation is inverted for resolutions equal to or higher than 100 m. In these cases, the output raster provides the GI generalization and is conducive to accurate and classification errors with the increase in cell size, but a solution to reduce this error is to increment the resolution, i.e., increase the number of cells (high resolution, small cells) [78]. Several other studies also reference the errors associated with vector-to-raster conversions and vice versa [83–85].

The differences in area for each LUC type presented in Table 6 are very small in terms of percentage, but these values represent several hectares in the study area (1% ≈ 88,971.3 ha), and thus some care is required in the analysis of results.

Crossing factors K_c and PA_{Rt} with absolute and relative variations of vector GI verses different resolution outputs, only the relative variations present a few significant correlations with these factors (Table 7). A more detailed analysis of these results highlights the high positive correlation between the CLC with PA_{Rt} (except RC Vet/R200 of CLC12), while K_c presents only a high correlation between the relative variations on lower resolution verses vector GI (RV Vet/R200).

Table 7. Correlation coefficients between K_c average, PA_{Rt}, and relative variations (RV) area of the vector GI (Vet) verses different resolution (R) outputs (significance level $p < 0.05$).

LUC Dataset	Variable	RV Vet/R10	RV Vet/R25	RV Vet/R50	RV Vet/R100	RV Vet/R200
CLC06	K_c	−0.28	0.58	0.41	−0.11	0.71
	PA_{Rt}	0.84	0.70	0.71	0.91	0.55
CLC12	K_c	−0.25	0.36	0.34	−0.35	0.72
	PA_{Rt}	0.96	0.82	0.68	0.73	−0.24
COS07	K_c	−0.54	−0.23	−0.54	−0.60	0.68
	PA_{Rt}	0.12	−0.29	0.32	0.40	−0.33
COS10	K_c	−0.58	−0.27	−0.57	−0.56	0.74
	PA_{Rt}	0.10	−0.31	0.32	0.28	−0.54

On the other hand, analyzing the results by principal component analysis (PCA), LUC class groupings derived from relative variations of area between different raster outputs and vector GI were observed (Figure 6).

In Figure 6, Factor 1 represents the relative variations mentioned above, and Factor 2 represents the factor form of polygons and their representation/distribution by LUC classes. LUC classes with lower relative variations tend to group together (G1), as well classes with highest relative changes (G2), and a few classes that do not fit into these groups represent the very high relative variations, but also influence the factor form of the polygons.

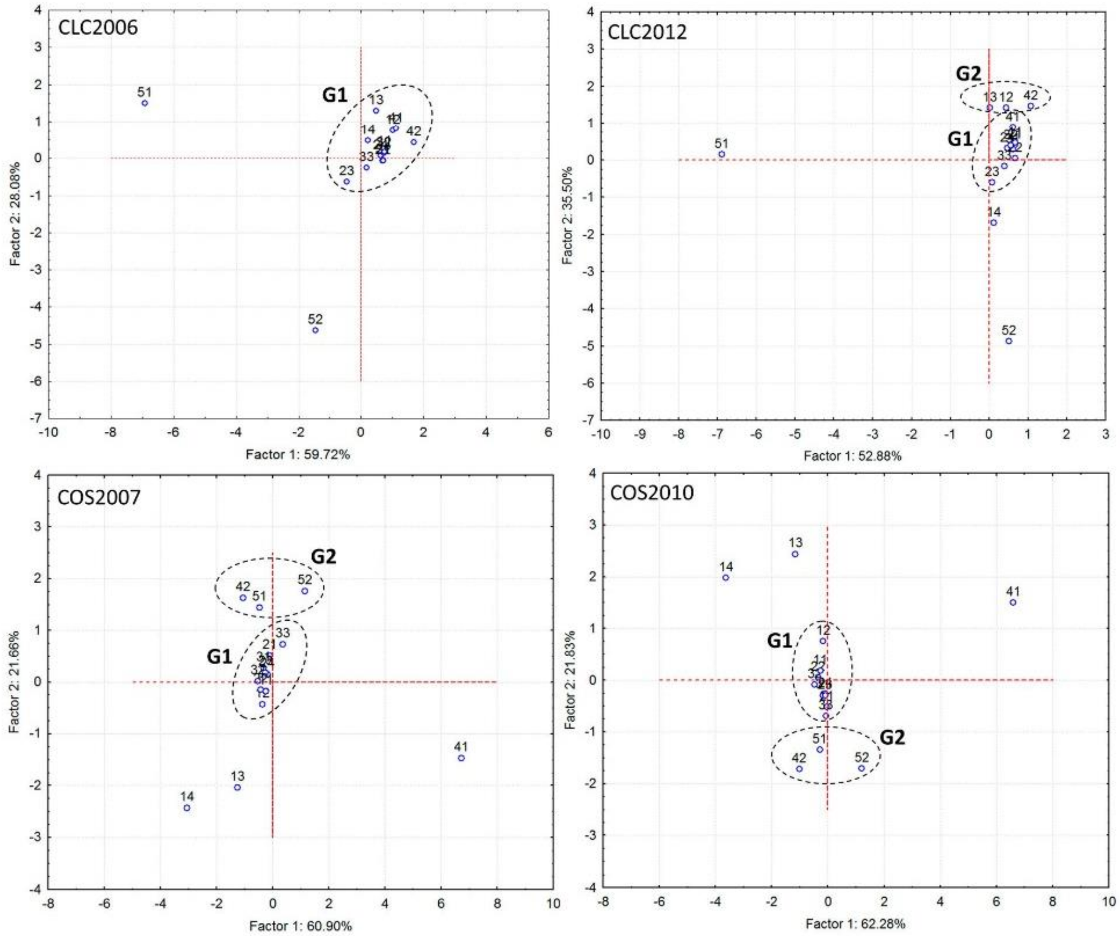

Figure 6. LUC class projection on the factor plane (LUC classes with sum of cosine squared ≥ 0). LUC codes: See legend in Figure 1.

5.4. LUCC Variations

In the first stage and considering data inputs for this analysis, the high correlation between the total areas of LUC types (for each LUC dataset) described initially, observed at the end of each period (three and six years for the COS and CLC, respectively), are questionable, because each LUC class can have area loss, and at the same time area gain for another LUC type, balancing the area of LUC classes. However, LUCC can also occur between subclasses (level 3 in CLC, or levels 4 and 5 in COS), although they were not described in this research, and we should have some caution in interpreting the relationship between the total area observed initially and the area observed at the end of the LUCC period. In this context, it is important to analyze the confusion matrix, using classes at level 2 of the nomenclature or at more detailed levels.

The results of the total area for each LUC class of COS and CLC (Table 4) are not consistent in a temporal sequence. These results are mainly due to the different properties of the LUC datasets, although each dataset has a different data acquisition year, but coincident with a part of the total period under evaluation. The CLC, with 25 ha of minimum mapping unit (MMU) and 20 m of spatial resolution (SR), presents greater generalization compared to COS (MMU 1 ha; SR 0.5 m). This explains the differences in area for each type of LUC in both datasets in different years.

The Portuguese territory presents great LUC fragmentation, especially in the northern region [39], where small plots (<25 ha) are predominant, and these are not identified in the CLC, while the COS, with smaller MMU and greater disaggregation of the nomenclature (five levels), enables identification and representation of the LUC with greater detail, and thus representation of most of these small plots (mostly agricultural parcels).

In the vector-to-raster conversion of LUC GI (cells with different sizes), some generalization of the GI occurs, which is demonstrated in this study and several others [48,56,86]. This generalization increases with cell size, making the results change, and the total area of each LUC type of the LUC datasets is analyzed. On the other hand, errors increased with increasing raster resolution [63] and the results presented also demonstrate this fact, especially the results at low resolution (100 and 200 m).

Comparing the different raster outputs with different resolutions, in general, the variations in area for LUC types are very similar, showing a high positive correlation, but the high-resolution area of LUC shows greater resemblance to what is observed in the vector GI (Table 8). The biggest areal differences between the areas in the vector and at different raster resolutions are for resolutions bigger than 50 m.

Table 8. Correlation coefficients between LUCC table transition areas with different resolutions (R) and vector data of CLC (bold values) and COS (significance level $p < 0.05$).

	R 10 m	R 25 m	R 50 m	R 100 m	R 200 m	Vector
R 10 m	1	0.999999999	0.999999997	0.999999943	0.999999738	1.000000000
R 25 m	**1.000000000**	1	0.999999996	0.999999937	0.999999741	1.000000000
R 50 m	**1.000000000**	**0.999999999**	1	0.999999951	0.999999698	0.999999997
R 100 m	**0.999999992**	**0.999999992**	**0.999999991**	1	0.999999632	0.999999942
R 200 m	**0.999999935**	**0.999999935**	**0.999999934**	**0.999999913**	1	0.999999735
Vector	**1.000000000**	**1.000000000**	**1.000000000**	**0.999999992**	**0.999999934**	1

Analyzing in detail the absolute variation in area of every LUC type in each dataset and for each year, different trends can be observed in area variation when cell size increases. These differences are more evident mainly in the classes with greater area in the different LUC datasets, i.e., scrub and/or herbaceous vegetation associations and forest, except for COS 2010, where the largest variations in the class “urban fabric and industrial, commercial and transport units” are remarkable.

The urbanized land and building infrastructure (roads, industrial complexes, etc.) increased between 2007 and 2010 in mainland Portugal, and much of this LUC type is identified in the COS. However, since this LUC type is very fragmented (particularly urban fabric) and has a specific geometry, generalization of these LUC types during the vector-to-raster conversion can have variable effects. For example, with increasing cell size, two or more parcels of artificial land can be aggregated, and with a higher resolution raster this is not reflected, because of the distance between the two polygons, and their respective size. Meneses et al. [87] observed in the Zêzere watershed (central Portugal) variations in artificial land GI outputs after several vector-to-raster conversions, referencing the importance of building dimensions, especially in outputs with large cell size. Other raster effects in the generalization process can occur, e.g., simplification and displacement of buildings [88].

The differences between LUCC areas observed in this research for the same classes show the effects resulting from vector-to-raster conversions at different resolutions, but also the importance of the GI properties, especially the scale, of each LUC dataset. For example, in the LUCC analysis, the case of the component “area gain” of each LUC type in the different LUC datasets, and the COS classes with the smallest area (e.g., urban fabric; mine, dump, and construction sites; non-artificial agricultural vegetated areas), because they present, in general, lower values of area gain (in relation to the results obtained by vector GI) when increasing the cell size of the raster outputs. For more generalized LUC GI, as in the case of CLC, the classes with small area do not stand out; in this case, the “Permanent crops” class presents the highest area increase and the “Arable land” class the largest area reduction compared to the vector GI areas (Figure 7). In the component “area loss” for each LUC type, highlight in the COS dataset the smaller area loss in the class “Pastures” for the raster with 200 m resolution (compared to vector GI); while in CLC, the class “Permanent crops” stands out with the highest difference (lowest reduction) between the raster at 200 m and what is obtained with the vector GI.

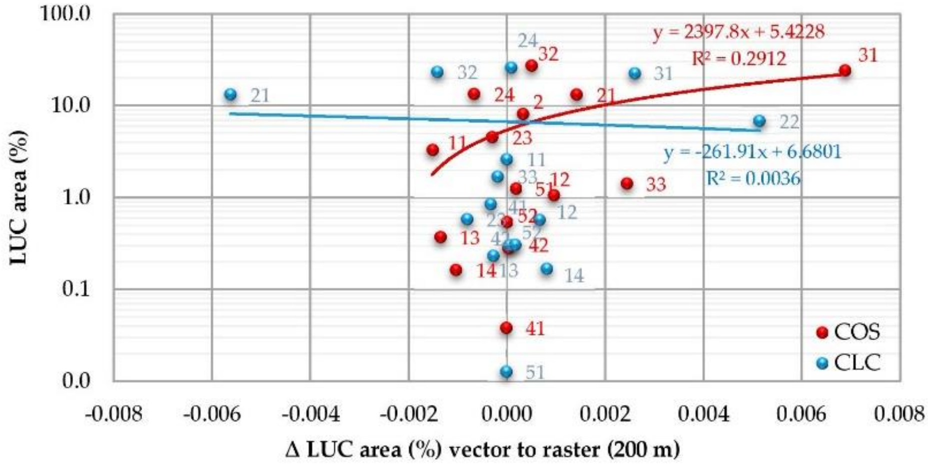

Figure 7. Relationship between LUC area (average area of vector GI: COS 2007, COS 2010; and CLC 2006, CLC 2012) and LUCC area (gains) variation obtained between vector and raster (resolution 200 m). See LUC legend (numbers) in Figure 1.

During the vector-to-raster conversion process, the representation depends on the area, but also the form of the polygons. For example, if the area of the Zêzere River presented in Figure 4 was represented in a compact form (circle), there would be more pixels with this attribute in lower-resolution outputs. This process can be seen as evidence of the faster raster LUCC calculations and other advantages of raster GIS, but vector methods provide higher accuracy [64]. However, high-resolution raster presents results very similar to vector GI.

Jaakkola [46] researched the quality of multiscale land cover data, also using CLC GI, and reported that the generalization process reduces the complexity of the data structure and adds error to the database, therefore the quality is always deteriorated in favor of simplicity and legibility. This author also found errors produced by the generalization of raster GI and refers to the tendency for area decrease for classes covering small areas, while the classes covering large areas with large average feature size tend to suffer an area increase. In fact, these observations have been confirmed by some results obtained in this research, namely the results using CLC. These results, however, differ slightly from the results obtained with COS, where area gain and area loss are very similar using high-resolution raster, without a well-defined trend when the cell size increases. This is mainly due to the GI scale of each LUC dataset, because the COS presents, for a LUC class, more fragmented polygons (due to the MMU), while the CLC is more generalized and presents, naturally, larger polygons.

Other authors, such as Veregin and McMaster [56], reported that changes in the thematic content of maps have implications on thematic accuracy and data quality in general. The results obtained here confirm this, because overall it was found that those datasets with the low-resolution raster (e.g., 100 and 200 m) differ from the vector GI results, due to multiple effects of the vector-to-raster conversion and GI properties.

6. Conclusions

In mainland Portugal, large LUCC were observed in the classes “forest and scrub and/or herbaceous vegetation associations” and “heterogeneous agricultural areas.” However, the LUCC results are not coherent among themselves when using the different resolutions of the two raster datasets considered (COS and CLC), and are very variable for different LUC classes. The results of the vector-to-raster conversion LUC GI (using different resolutions) show differences for LUC areas in the Portuguese territory. These results highlight the generalization of GI that occurs in these conversion processes. Variations of LUC area by changing the cell size of different LUC datasets (COS or CLC for several years) were observed, but these variations were not linear (which was expected in the first place) and not consistent among LUC classes in each LUC dataset, especially the outputs with a resolution equal to or higher than 100 m.

Furthermore, different results between LUC datasets with different properties were observed. COS is more detailed than CLC, and their GI has partial temporal coincidence (for the LUC years selected), but the LUCC results obtained were different in the territory covered by this study. These results can highlight the differences in study period between the features of the LUC datasets.

The generalization that occurs in the vector-to-raster conversion process is also shown and, in this process, the importance of the inherent details of the GI vector in each LUC dataset, especially the amalgamation and dilation, form, and area of the polygons. In this sense, we stress the importance of the GI properties, because the detail is important in explaining the results obtained on LUCC determinations.

Higher resolutions of LUC GI (e.g., 10, 25, or 50 m) are better for LUCC analysis in large territorial extensions, even at the scale of a country, as in this case study (mainland Portugal), because the differences observed between these raster outputs have a high correlation with results obtained by vector GI. However, 50 m resolution is suggested for LUCC assessment in this country, because this raster dataset with this resolution has advantages in terms of storage space compared to higher resolutions. In summary, for each case study or procedure, we should balance the efficiency of processes against the best accuracy of results.

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Conflicts of Interest: We hereby declare that the work presented in this paper is an original research carried out by all authors. All the research stated on the paper, which has not been carried out by us, has been fully acknowledged. All appropriate ethics and other approvals have been obtained for this research. The authors declare no conflict of interest.

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Effects of different land use and land cover data on the landslide susceptibility zonation of road networks

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Abstract. This work evaluates the influence of land use and land cover (LUC) data with different properties on the landslide susceptibility zonation of the road network in the Zêzere watershed (Portugal). The information value method was used to assess the landslide susceptibility using two models: one including detailed LUC data (the Portuguese Land Cover Map – COS) and the other including more generalized LUC data (the CORINE Land Cover – CLC). A set of fixed independent layers was considered as landslide predisposing factors (slope angle, slope aspect, slope curvature, slope-over-area ratio, soil, and lithology) while COS and CLC were used to find the differences in the landslide susceptibility zonation. A landslide inventory was used as a dependent layer, including 259 shallow landslides obtained from the photointerpretation of orthophotos from 2005, and further validated in three sample areas. The landslide susceptibility maps were assigned to the road network data and resulted in two landslide susceptibility road network maps. The models' performance was evaluated with prediction and success rate curves and the area under the curve (AUC). The landslide susceptibility results obtained in the two models present a high accuracy in terms of the AUC (>90 %), but the model with more detailed LUC data (COS) produces better results in the landslide susceptibility zonation on the road network with the highest landslide susceptibility.

1 Introduction

Landslides are natural processes that can constrain the free movement of people and goods when they directly or indirectly affect road networks (Bíl et al., 2014, 2015; Hilker et al., 2009; Meneses, 2011; Winter et al., 2013). The total or partial blockages of road networks have economic and societal impacts, particularly on the direct damage to the infrastructure (material damages), on the population (injuries and deaths) when driving on the affected infrastructure (Guillard and Zêzere, 2012; Pereira et al., 2014, 2017), or by causing indirect damages, such as delays, detours, material damage, and the rising prices of raw materials (Zêzere et al., 2008; Bíl et al., 2014, 2015; Jenelius and Mattsson, 2012; Winter et al., 2016).

Landslide susceptibility assessment is crucial to identifying locations with higher probabilities of landslide occurrence (Conforti et al., 2014; Guillard and Zêzere, 2012; Guzzetti et al., 2006; Pereira et al., 2014; van Westen et al., 2008). Landslide susceptibility is the likelihood of a landslide occurring in an determined area controlled by local terrain conditions; it may also include a description of the velocity and intensity of an existing or potential landslide (Fell et al., 2008; Günther et al., 2013; Guzzetti et al., 1999). Landslide susceptibility reflects the degree to which a terrain unit can be affected by future slope movements (Günther et al., 2013).

In general, the choice of landslide predisposing factors and the main details of the geographical information are not explained in a landslide susceptibility assessment based on statistical methods; rather, criteria defined in the literature (e.g., slope angle, slope aspect, slope curvature, soil, lithology, land use, and land cover) are used for this selection because they can explain the occurrence of slope movements in the study area (Blahut et al., 2010; Castella et al., 2007; Castellanos Abella, 2008; Guzzetti et al., 1999, 2006; Soeters

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and van Westen, 1996; van Westen et al., 2008; Zêzere et al., 2008, 2017).

Beyond the influence of different environmental factors (e.g., lithology, slope angle, slope morphology, topography, soils, and hydrology) on the spatial distribution of landslides, land use and land cover (LUC) dynamics are also an important factor on landslide susceptibility assessment (Guillard and Zêzere, 2012). Certain land use and land cover changes (LUCCs) (e.g., deforestation, slope ruptures to road construction, steep slopes) increase the number of unstable slopes (Reichenbach et al., 2014), i.e., promoting the propensity for landslide occurrence, and can have an important impact on landslide activity (Beguería, 2006; Glade, 2003; Mugagga et al., 2012; Persichillo et al., 2017; van Westen et al., 2008).

The LUC, while a proxy variable, is very dynamic over time and is influenced by climate-driven changes and direct anthropogenic impacts (Promper et al., 2014). In this regard, it is an important predisposing factor to landslide susceptibility assessment, and Dymond et al. (2006) mention that importance: "the quality of the input land-cover map is important because the main purpose of the landslide susceptibility model is to identify where land cover needs to be changed."

For instance, performing a landslide susceptibility analysis with a historical inventory over long periods (e.g., decades) demands the use of a permanent set of predisposing factors along the landslide inventory timeline. LUC can change over time; for this reason, it will be more accurate to use the LUC for different periods (Reichenbach et al., 2014) than using the most recent LUC map, to avoid spatial relations between past slope instability and incorrect LUC classes.

The scale of the predisposing factors directly influences the map elements' representation and detail, as well as the choice of the scale of analysis of the final results (Leitner, 2004; Stoter et al., 2014). The choice in the level of detail will also constrain the modeling results. For example, Meneses et al. (2018b, c) obtained different LUCC results in Portugal due to the use of different LUC datasets, namely the CORINE Land Cover (CLC) and the official Land Cover Map of Portugal (Portuguese designation and acronym *Carta de Ocupação do Solo*, COS), with different properties concerning the scale (1 : 100000 and 1 : 25000, respectively), minimum mapping unit (25 and 1 ha, respectively), and generalization level (Table 1).

Due to the variation in the road network morphology (the length vs. width of the roads), the selection of appropriate data that integrate the analysis of road blockages caused by landslides requires a systematic assessment of the detailed properties of the landslide predisposing factors (Drobnjak et al., 2016; Imprialou and Quddus, 2017; Kazemi and Lim, 2005; Orongo, 2011) to obtain detailed landslide susceptibility results at the local scale (roads).

In this context, the main goal of this work is to evaluate the influence of the LUC data properties on the landslide susceptibility zonation of road networks. Two specific goals were defined: (i) to evaluate and quantify the landslide susceptibility results using two LUC datasets (CLC 2006 and COS 2007) with different properties (scale and minimum mapping unit) in two landslide susceptibility models; (ii) to use the output results of the two landslide susceptibility models to identify the sections of the main road network with the highest landslide susceptibility that will suffer future road blockages.

2 Materials and methods

2.1 Study area

This study was performed in the Zêzere watershed (5063.9 km^2) located in the center region of mainland Portugal (Fig. 1). The north-northwest sector of this watershed is occupied by the Serra da Estrela, reaching a maximum elevation of 1993 m, where steep slopes can be found; in the central sector, the relief is less irregular when compared to the previous sector, but it still has steep slope areas (e.g., the vicinity of the Castelo de Bode and Cabril reservoirs); in the south-southwest sector, gentle slopes and flat areas are predominant.

The soils of the Zêzere watershed are very variable among the north-northwest, center, and southwest sectors. In the northwest sector, Cambisols predominate, with small areas of Fluvisols and eutric Lithosol along the Zêzere River. In the central area, Lithosols are dominant, with some areas of Cambisols. In the south-southwest sector, there are areas of Lithosols intercalated with Cambisols and Luvisols.

According to CLC 2006, the predominant types of LUC in the study area are forest and seminatural areas, which represent 72 % of the watershed area. Other LUC types are less representative, for example, agricultural land (25.5 %), artificialized land–urban areas (1.5 %), and water bodies (1 %), including an important freshwater reservoir, the Castelo de Bode dam (Meneses et al., 2015a). The LUC of this watershed is very dynamic, highlighting the LUCC in forest and agricultural areas derived from multiple socioeconomic driving forces (Meneses et al., 2017) and the degradation of vast forest areas by wildfires (Meneses et al., 2018a).

Due to the large extension of this watershed, three sample areas were selected according to the high density of landslides observed in these locations: the Serra da Estrela, Vila de Rei, and Ferreira do Zêzere municipalities (areas of 86.7, 191.5, and 190.4 km^2, respectively), where fieldwork was developed to validate part of the landslide inventory and the disruption of roads caused by landslides.

2.2 Data

The landslide predisposing factors used to model the landslide susceptibility in the Zêzere watershed were selected after reviewing the literature about the causal factors of landslide occurrence (Blahut et al., 2010; Castella et al., 2007;

Table 1. Properties of LUC data.

Properties	Land cover maps of Portugal	CORINE land cover
Acronym	COS	CLC
Scale	1 : 25 000	1 : 100 000
Minimum mapping unit	1 ha	25 ha
Data structure	Vector	Vector
Geometry	Polygons	Polygons
Minimum distance between lines	20 m	100 m
Base data	Orthophotos	Satellite images
Spatial resolution	0.5 m	20 m
Nomenclature	Hierarchical (five levels)	Hierarchical (three levels)
	225 classes	44 classes
Production method	Visual interpretation	Semiautomated production and visual interpretation
Date of production	2007	2006

Castellanos Abella, 2008; Guzzetti et al., 1999; Reichenbach et al., 2018; Soeters and van Westen, 1996; van Westen et al., 2008; Zêzere et al., 2008, 2017) (Fig. 2).

Six fixed landslide predisposing factors were considered: slope angle, slope aspect, slope curvature, slope-over-area ratio (SOAR), soil, and lithology. The LUC types of COS and CLC were used to find the differences in the landslide susceptibility zonation. The set of landslide predisposing factors and the corresponding classes (Fig. 2) were the same in all models, only changing the LUC data.

In general terms, an increasing slope angle promotes landslide occurrence and is a very good proxy of the shear stress (Zêzere et al., 2017). Slope instability is more frequent at the higher slope angles of the Serra da Estrela and throughout the Zêzere River valley. Also, in these areas, convex slope curvature is predominantly related to slope instability. The slope aspect is important in the spatial distribution of the different LUC types of the study area (Fig. 2) and in slope instability, especially in northwest-facing slopes (more exposed to rain and with higher humidity levels).

The SOAR is a proxy variable of the moisture retention, the soil water content, and the surface saturation zones (Zêzere et al., 2017), highlighting, in the Zêzere watershed, the upstream (very close to the Zêzere River) and southwest areas with a higher SOAR.

In the sample areas of the Vila de Rei and Ferreira do Zêzere municipalities, where a high landslide density was observed, schist and metasedimentary lithologies are predominant. Further, slope instability in the watershed is higher in the hortic Luvisols and in the LUC classes of forest and shrubland or herbaceous vegetation associations (Fig. 1).

The official LUC data available for the study area are CLC produced by the European Environment Agency (EEA) and COS produced by the General Directorate for Territorial Development (DGT) in Portugal. These LUC data (CLC and COS) have different properties and have been used in several studies about landslides in Portugal (e.g., Guillard and Zêzere, 2012; Meneses et al., 2015b; Piedade et al., 2011; Reis et al., 2003; Zêzere et al., 2017).

Table 1 describes the main properties of these LUC data (DGT, 2013; EEA, 2007; IGP, 2010). Among the differences between the two LUC datasets, the scale is highlighted because COS is the most detailed relative to CLC (proportion 1/4). However, the properties are not proportional between the two LUC datasets; while the COS features have a minimum mapping unit of 1 ha, CLC has a minimum mapping unit of 25 ha, and the minimum distance between lines is 20 m in COS, while in CLC it is 100 m.

To reduce possible discrepancies in the field, the LUC data were collected for near dates: CLC 2006 and COS 2007. The LUC data were developed with base information that matches in temporal terms, for example, the satellite images, orthophotos, and agricultural and forestry inventories used as auxiliary information. The nomenclature of these LUC data corresponds to the third level (see the official CLC nomenclature on the EEA website). In this study, the second level of the CLC nomenclature was used because it has a lower number of classes for the study area (12 of 31 classes).

The agreement among the LUC data is presented in Table 2. The forest class shows great differences between the two LUC datasets. For example, COS represents more forest area relative to CLC (34 % and 26.9 % of the study area,

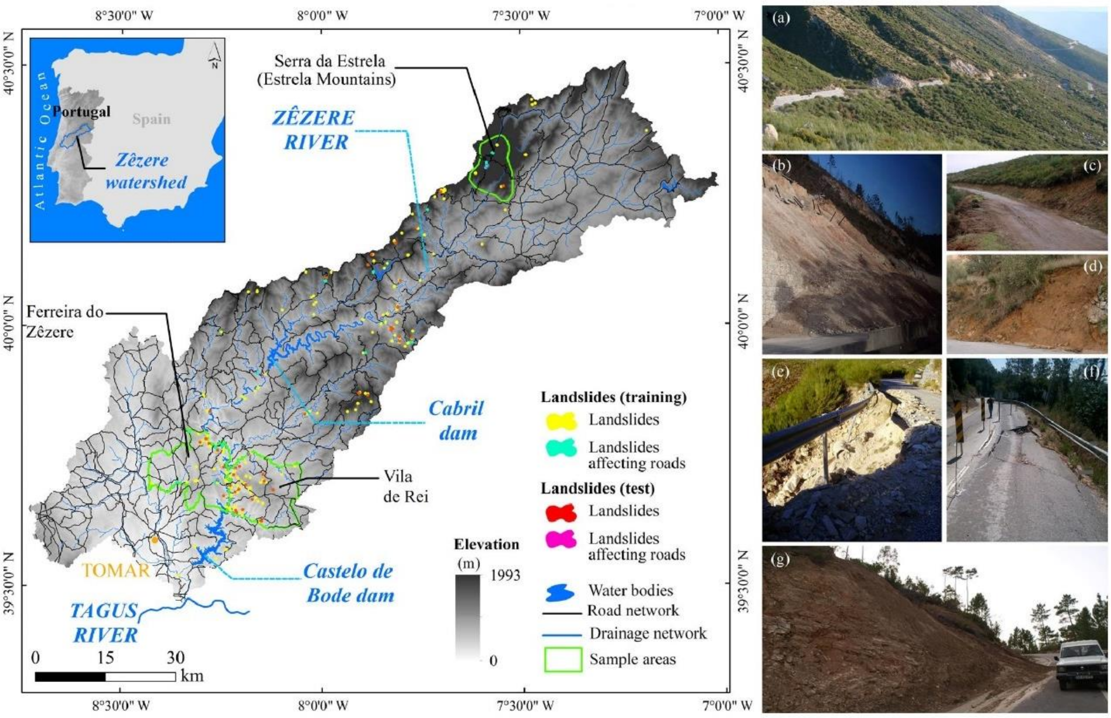

Figure 1. Zêzere watershed and landslide inventory. The pictures represent landslides that affected roads: A, B, C, D, and E – municipality roads of Serra da Estrela; F – Ferreira do Zêzere; G – Vila de Rei.

respectively) because a part of COS (approximately 10 % of the study area) is classified as scrub and/or herbaceous vegetation associations in CLC. The reverse was also verified; approximately 5 % of the study area is classified as scrub and/or herbaceous vegetation associations in COS, and this same area is represented by forest class in CLC. These discrepancies are derived from the LUC data properties because COS is more detailed and represents more degraded forest areas, especially where wildfires occurred. These events affected a large percentage of the watershed (Meneses et al., 2018a), especially the central sector, as a vast burned area culminated in a large transition of forest area to shrubland.

The forest, scrub and/or herbaceous vegetation associations and open spaces with little or no vegetation are the LUC types predominant in the hillsides with steep slopes (see Tables S1 and S2 in the Supplement). The remaining LUC classes present more area in the lower slopes ($>10°$).

The soil and lithology data were obtained from the environment atlas web platform published by the Portuguese Environment Agency (APA) at a 1 : 1 000 000 scale. A digital elevation model (DEM) was built using digital topographic maps at a 1 : 25 000 scale (IGEOE), containing contour lines with 10 m equidistance.

Slope angle, slope aspect, slope curvature, and SOAR (topographic wetness index) layers were extracted from the DEM. Road network data (vector lines) were extracted from Portugal's military cartography (itinerary maps, 1 : 500 000 scale), available on the Portuguese Army Geospatial Information Center's website. The road network was classified according to the roads' width and their network hierarchy. Considering the road center line, a buffer of 5 m was defined for municipal roads, 10 m for complementary roads, and 20 m for superhighways. These distances were measured with geographic information systems (GIS) on the study area roads (directly on the orthophotos).

The landslide inventory was obtained using photointerpretation (orthophotos from 2005 and Google Earth images), a process supported by the ancillary topographic data and further fieldwork validation only performed in the sample areas (Fig. 1) due to the extension of the study area. A total of 128 landslides (predominantly shallow translational slides), with a total area of 74 042 m^2, were validated during fieldwork in the sample areas (49.4 % of the total inventoried landslide cases). Among the landslides initially inventoried by photointerpretation in the sample areas, more than 90 % of cases

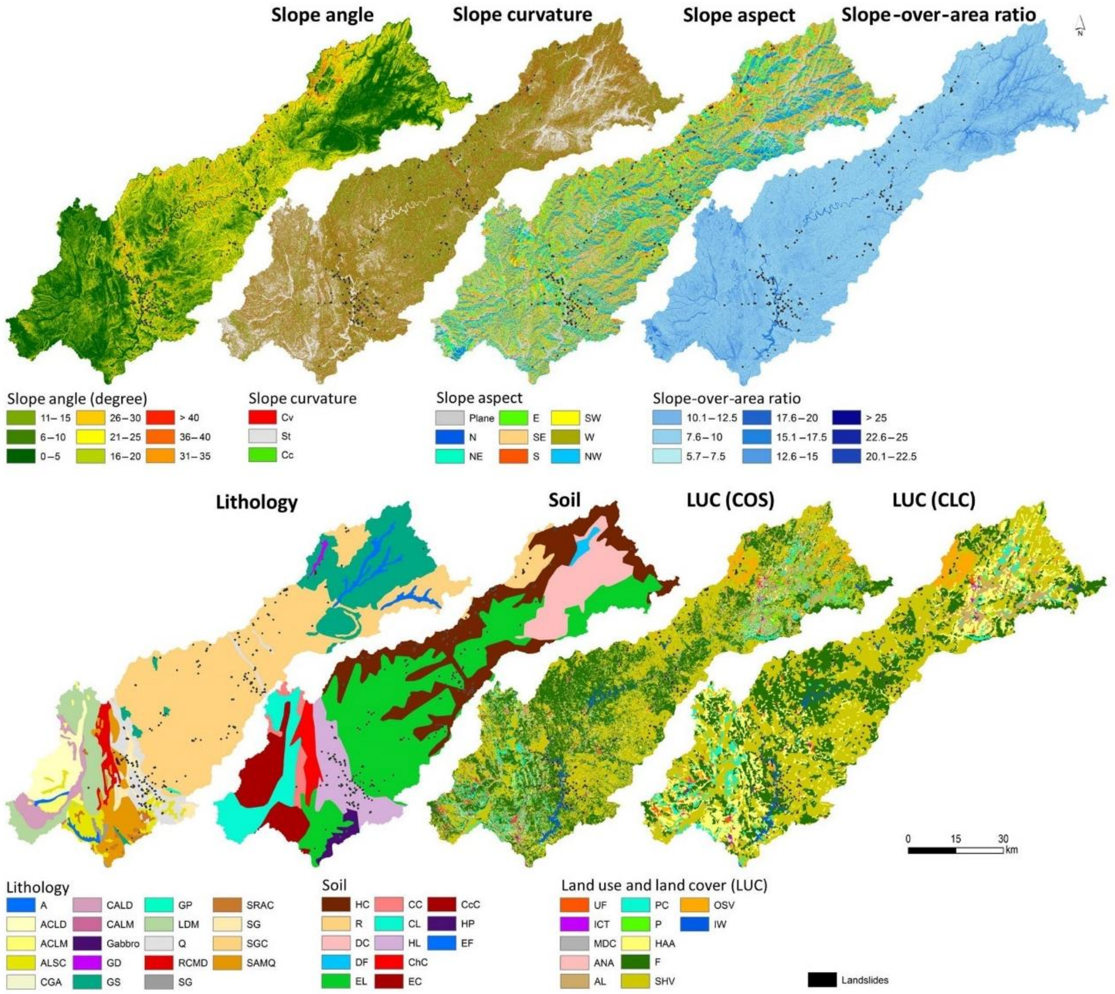

Figure 2. Predisposing factors used in the landslide susceptibility assessment. Predisposing factor map legend. Curvature – Cv: convex; St: straight; Cc: concave. Lithology – A: alluvium; ACLD: arenites, conglomerates, limestones, dolomitic limestone; ACLM: arenites, conglomerates, limestones, dolomitic limestone and marl; ALSC: arenites, limestone, sand, stony banks and clay; CGA: clayey schist, graywackes and arenites; CALD: conglomerates, arenites, limestone, dolomitic limestone, marly limestone and marl; CALM: conglomerates, arenites, white limestone and red marl; G: gabbro; GD: glacial deposits; GS: granite and other stones; GP: granite porphyritic; LDM: limestones, dolomitic limestone, marly limestone and marl; Q: quartzite; RCMD: red sandstone, conglomerates, marl and dolomitic limestones; SG: sands and gravel; SRAC: sands, rocky, arenites and clay; SG: schists and graywackes; SGC: schist and graywacke complex; SAMQ: schists, amphibolite, mica schists, quartzite graywackes, carboned stones and gneisses. Soil – HC: humic Cambisols; R: rankers; DC: dystric Cambisols; DF: dystric Fluvisols; EL: eutric Lithosol; CC: calcic Cambisols; CL: calcic Luvisols; HL: hortic Luvisols; ChC: chromic Cambisols; EC: eutric Cambisols; CcC: calcic–chromic Cambisols; HP: hortic Podzols; EF: eutric Fluvisols. LUC – UF: urban fabric; ICT: industrial, commercial and transport units; MDC: mine, dump and construction sites; ANA: artificial, nonagricultural vegetated areas; AL: arable land; PC: permanent crops; P: pastures; HAA: heterogeneous agricultural areas; F: forests; SHV: scrub and/or herbaceous vegetation associations; OSV: open spaces with little or no vegetation; IW: inland waters.

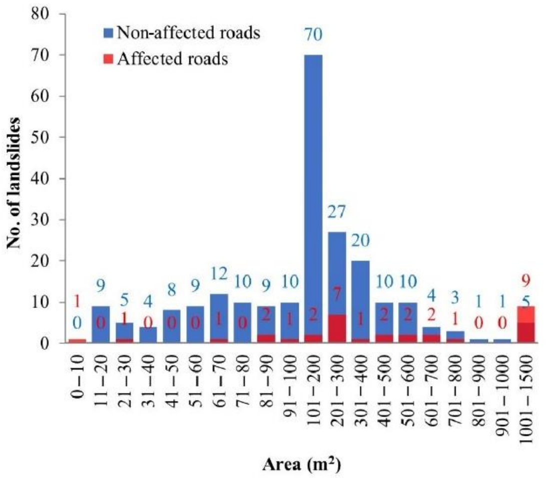

Figure 3. Landslide size frequency distribution.

Table 2. LUC data agreement (area in hectares) between CLC and COS classes.

Data / CLC	COS: Urban fabric (UF)	Industrial, commercial, and transport units (ICT)	Mine, dump, and construction sites (MDC)	Artificial, non-agricultural vegetated areas (ANA)	Arable land (AL)	Permanent crops (PC)	Pastures (P)	Heterogeneous agricultural areas (HAA)	Forests (F)	Scrub and/or herbaceous vegetation associations (SHV)	Open spaces with little or no vegetation (OSV)	Inland waters (IW)	Total
UF	3160.2	439.8	77.3	100.8	207.7	502.0	15.7	929.2	337.7	251.5	0.1	18.7	6 040.7
ICT	134.1	650.4	83.0	9.5	33.4	27.4	9.0	62.5	130.8	207.7	0.3	8.1	1356.1
MDC	6.1	58.3	283.0	0	3.6	3.6	6.8	6.5	48.2	53.5	0.2	5.4	475.0
ANA	29.3	2.9	0	22.5	0	0	0	0	1.7	9.1	0	0	65.6
AL	245.3	171.7	25.0	12.2	9166.1	1304.4	2225.0	1317.1	1133.2	1435.9	51.0	190.7	17 277.5
PC	1271.4	93.3	37.3	21.2	1357.9	7948.5	315.4	2930.0	2004.5	2300.2	7.9	38.1	18 325.7
P	4.4	2.4	0	0	61.3	0.9	36.1	58.4	41.2	188.6	0	0	393.2
HAA	7791.6	736.5	271.4	73.7	11 773.1	15 553.2	2341.0	23 762.4	16 514.4	12 935.5	143.3	243.9	92 140.0
F	745.3	392.9	173.1	29.3	741.9	1715.5	238.1	4058.7	100 486.5	26 805.7	42.0	735.8	136 164.8
SHV	826.5	510.0	259.3	38.0	1353.1	2543.2	958.3	5832.8	50 509.8	149 644.0	4052.8	846.7	217 374.5
OSV	29.4	13.8	5.3	1.4	18.3	10.3	10.7	140.4	860.0	6367.1	4206.6	30.3	11 693.7
IW	5.6	12.0	0	0.2	1.3	7.5	0	15.2	278.5	180.7	2.4	4589.5	5093.0
Total	14 249.1	3084.1	1214.7	308.8	24 717.7	29 616.3	6156.0	39 113.2	172 346.6	200 379.5	8506.6	6707.1	506 399.7

were confirmed. In these sample areas, road disruptions were also validated.

For the complete Zêzere watershed, 259 landslides were identified, predominantly of shallow type. Of the total, 32 landslides directly affected the road network (total or partial blockages by the material and seven cases with partial loss of infrastructure). The landslide inventory was randomly divided into two subsets (Fig. 1) (Chung and Fabbri, 2003): the landslide training group and the landslide test group (81.5 % and 18.5 % of the total landslide affected area, respectively). The statistical description of each landslide group is presented in Table 3.

The landslide size frequency distribution is different between the landslides that affected the road network and those that did not (Fig. 3). The area of the majority of landslides ranges between 101 and 200 m^2, while most of the landslides that affected the road network present a larger area (>1000 m^2).

All the predisposing factors and landslide inventory were converted to raster (resolution 10 m) to assess the landslide susceptibility. The selection of the predisposing factors' cell size was based on several geoinformation conversion tests in the Zêzere watershed previously performed by Meneses et al. (2016, 2018b).

2.3 Methods

The landslide susceptibility modeling was carried out using the information value (IV) method (Yan, 1988; Yin and Yan, 1988). The IV method is a bivariate statistical method that has been used in several studies and different areas with good results for landslide susceptibility assessment (e.g., Guillard and Zêzere, 2012; Oliveira et al., 2015a; Zêzere et al., 2017).

Table 3. Statistics description of the training group and test group landslide inventories.

	Training group		Test group		
	Non-affected roads	Affected roads	Non-affected roads	Affected roads	Total inventory
Total landslides	185	26	42	6	259
Total area (m^2)	44 604	369 404	10 444	12 089	104 077
Minimum (m^2)	134	7	18	82	7
Maximum (m^2)	27 364	12 507	1911	5881	12 507
Mean (m^2)	2414	1421	249	2015	402
Standard deviation (m^2)	3284	2647	304	2627	1069

The IV of each class within each explanatory variable is given by Eq. (1) (Yan, 1988; Yin and Yan, 1988):

$$\mathrm{IV}x_i = \ln \frac{S_i/N_i}{S/N}, \tag{1}$$

where $\mathrm{IV}x_i$ is the IV of the variable x_i, S_i is the number of terrain units with landslides and the presence of variable x_i; N_i is the number of terrain units with variable x_i, S is the total number of terrain units with landslides, and N is the total number of terrain units.

The IV method was applied in several landslide susceptibility zonation studies, providing good results (e.g., Che et al., 2012; Chen et al., 2016; Conforti et al., 2012) at the regional scale. This method was also applied in several studies conducted in Portugal, with good performance in susceptibility assessment (e.g., Guillard and Zêzere, 2012; Oliveira et al., 2015b; Pereira et al., 2014; Zêzere et al., 2017).

The a priori probability of finding a landslide unit in the study area (S/N) and conditional probabilities for each class of the independent variables (S_i/N_i) were calculated, obtaining the IV for these classes. However, the IV method presents constraints on obtaining the natural logarithm for negative results; in this case, the lower value calculated for each variable was assigned to classes when S_i was equal to zero.

The IVs of all the variables were combined to obtain the landslide susceptibility map (LSM). For the final landslide susceptibility assessment, i.e., the integration of the IVs of all the independent variables, the following equation was considered:

$$\mathrm{IV}_j = \sum_{i=0}^{n} X_{ij} I_i, \tag{2}$$

where IV_j is the total IV of the cell j, I_i is the information value of each cell of each independent variable, n is the number of variables, and X_{ij} assumes the value 1 or 0, depending on the presence or absence of the variable in the terrain unit.

Landslide susceptibility model performance was assessed using training landslides. Landslide areas in the test group were only used to perform an independent validation of the landslide susceptibility. Prediction rate curves (PRCs) were computed for each final LSM (Chung and Fabbri, 1999, 2003) and also the area under the curve (AUC). Success rate curves (SRCs) were obtained for the landslide susceptibility road network maps using only the landslides that affected roads.

The importance of each independent variable in the landslide susceptibility assessment was also determined, so that the spatial influence of each predisposition factor in the models can be understood. The accountability ($\mathrm{A_I}$) and reliability ($\mathrm{R_I}$) indexes have been used in different contexts to assess the importance of each independent variable in the bivariate statistical methods (e.g., Blahut et al., 2010; Meneses et al., 2016). $\mathrm{A_I}$ explains how different classes of predisposition factors are relevant in the analysis because they contain the landslide area, while $\mathrm{R_I}$ depends on the average density of the landslide area in the predisposing factor classes that are more relevant to the development of this process. In this procedure, the $\mathrm{A_I}$ and $\mathrm{R_I}$ were determined using Eqs. (3) and (4), respectively (Blahut et al., 2010).

$$\mathrm{A_I} = \frac{\sum_{i=1}^{n} k}{N} 100 \tag{3}$$

$$\mathrm{R_I} = \frac{\sum_{i=1}^{n} k}{\sum_{i=1}^{n} y} 100 \tag{4}$$

Here k is the landslide area in classes with the conditional probability values higher than a priori probability, N is the total landslide area, and y is the area of each class of independent variable with a conditional probability above the a priori probability.

Two landslide susceptibility models were built using the IV method (see results in Table S3), using the same set of predisposing factors, except the LUC data (Fig. 4): model 1 (M1) was modeled with COS 2007 and resulted in landslide susceptibility map 1 (LSM1); model 2 (M2) was modeled with CLC 2006 and resulted in landslide susceptibility map 2 (LSM2). LSM1 and LSM2 were correlated, and the corresponding spatial agreement was analyzed.

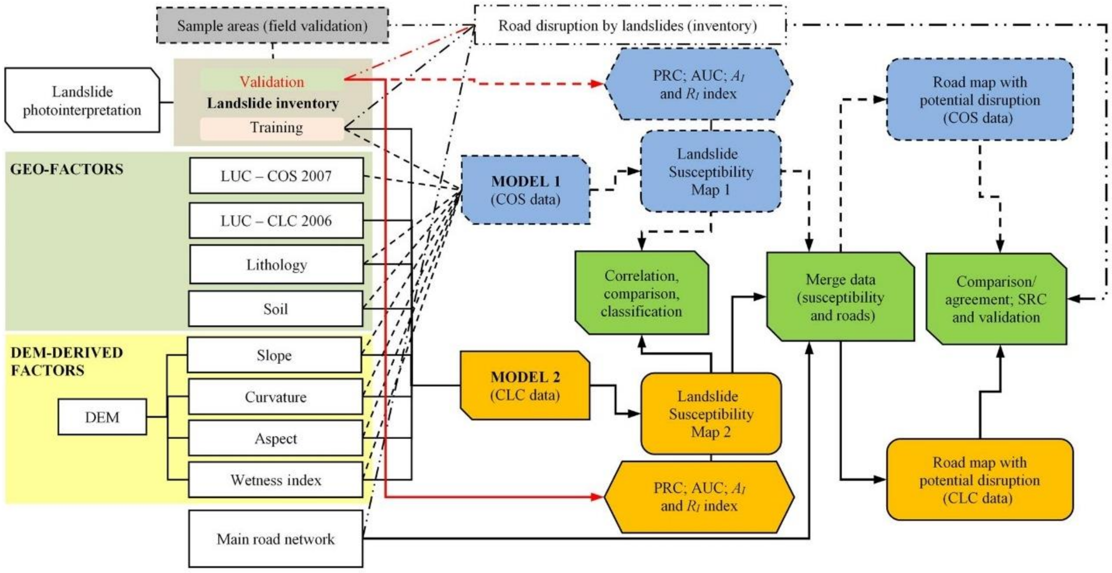

Figure 4. Workflow of landslide susceptibility assessment (using different LUC datasets) and the road susceptibility data integration.

Information values of LSM1 and LSM2 were assigned to the road network (using GIS), resulting in a road network map with the landslide susceptibility location (landslide susceptibility of the road network – LSRN1 and LSRN2), where there is a higher spatial probability of road interruption or road interference caused by landslides. Different outputs of the two models (road network) were compared using the overall agreement and kappa coefficient (Congalton and Green, 2009), allowing the assessment of the consistency and agreement of the obtained results with different LUC datasets. The information of road disruptions caused by landslides was used to validate these results.

Landslide susceptibility maps were built and classified in 10 classes (deciles) containing an equal number of terrain units to allow visual comparison of the results.

3 Results

3.1 Landslide susceptibility

The landslide susceptibility results show spatial contrasts in the study area. Some areas in the center of the watershed (highlighting the vicinity of the Castelo de Bode reservoir) and the northern sectors (highlight the Serra da Estrela) present the highest landslide density and susceptibility (Fig. 5).

The results of the A_I and R_I indexes show important differences among the predisposing factors that have been integrated in the landslide susceptibility models (Table 4). The

Table 4. Results of the accountability (A_I) and reliability (R_I) indexes.

Factors	A_I	R_I
Aspect	79.5	0.2
Slope	76.1	0.6
SOAR	13.5	0.7
Soil	62.4	1.0
Lithology	60.6	0.4
Curvature	61.1	0.3
LUC (COS)	82.0	0.3
LUC (CLC)	76.0	0.3

LUC predisposing factors (COS and CLC) registered the highest A_I results, highlighting COS's LUC types with a higher A_I. These results show the relevance of certain classes of COS in the predisposing factor dataset, by the number of landslide areas covered (emphasis on the forests, scrubland, and/or herbaceous vegetation associations, and open spaces with a scarcity or absence of vegetation).

The soil, SOAR, and slope angle present the highest values in the case of R_I, which shows that landslide density is concentrated in a reduced number of classes of each of the predisposing factor areas (e.g., hortic Luvisols, SOAR [22.5–25], and slope [between 25 and 45°]).

The landslide susceptibility model's agreement test was performed using the landslide training inventory used to perform the outputs of each landslide susceptibility model, and these results were validated using the landslide test group.

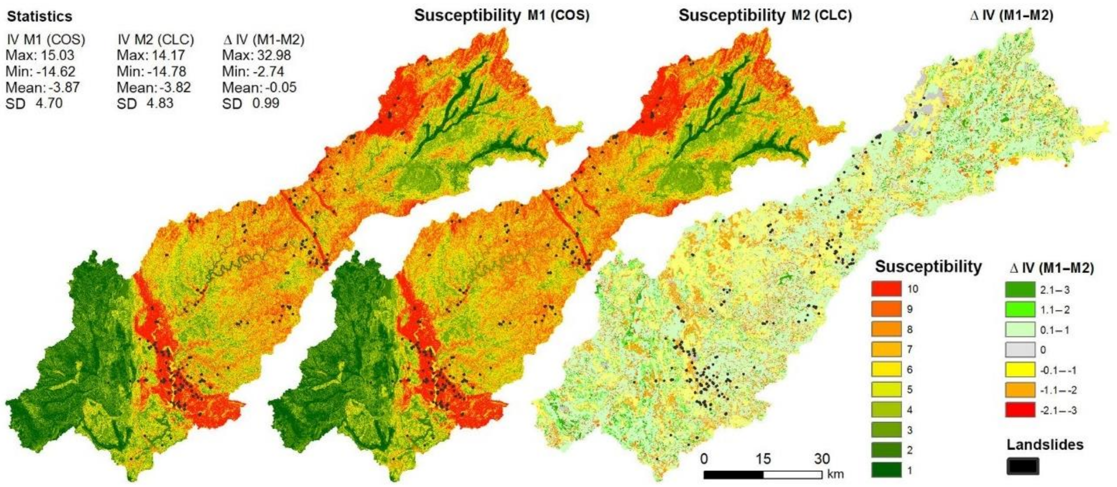

Figure 5. Landslide susceptibility (IV represented from the highest – red – to the lowest susceptibility – green): the map of Susceptibility M1 represent the results obtained with model 1 (performed with COS data) – LSM1; the map Susceptibility M2 represent the results obtained with model 2 (performed with CLC data) – LSM2. The map on the right is the variation between LSM1 and LSM2.

The PRCs of each final susceptibility map (obtained from the results of the landslide training group) show slight variations (Fig. 6), but, in general terms, the curves are identical, demonstrating the high and similar performance of the models in the determination of landslide-susceptible areas.

The AUC of LSM1 and LSM2 that includes the same landslide information used to train the models is 94.1 % and 93.9 %, respectively. These results (landslide prediction) were considered to integrate the landslide susceptibility road network (LSRN1 and LSRN2) and the next analyses presented. Additionally, spatial differences were observed in the landslide susceptibility maps (Fig. 5), reflecting the differences of the influence of LUC properties.

When the two landslide susceptibility maps are reclassified into two classes (not susceptible IV ≤ 0 and susceptible IV >0), the susceptible area in LSM1 corresponds to 19.7 % and in LSM2 to 20.8 %. The CLC data provide IV results lower than the IV obtained with the COS data, but CLC is more generalized and justifies that the most susceptible area is observed in LSM2, compared to LSM1. The variation between the maximum and minimum IVs (3 and -3 of ΔIV in Fig. 5) show the landslide susceptibility differences derived from spatial representation of LUC classes of the two LUC datasets considered. The highest variations between LSM1 and LSM2 are found in places with reduced IVs (low and moderate susceptibility), marking the central sector of the study area. The areas with the highest IVs in LSM1 and LSM2 present a lower variation.

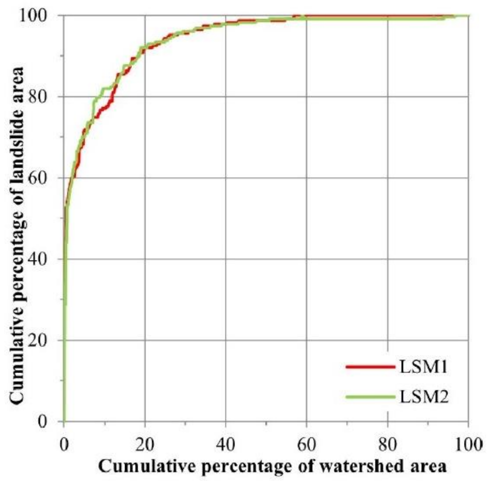

Figure 6. Prediction rate curves (PRCs) of the landslide susceptibility (LSM1 – COS and LSM2 – CLC).

3.2 Landslide susceptibility in the road network

Due to the width of the road network, in most cases, these infrastructures are not identified in the LUC data due to the properties or specifications (Table 1), namely, the minimum distance between lines considered in each LUC data in the research. The class "road and rail networks and associated land" (LUC nomenclature, level III) integrates the main class "industrial, commercial, and transport units" (level II); how-

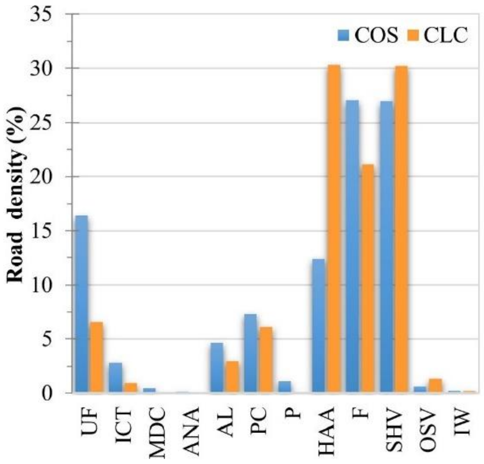

Figure 7. Density of roads by LUC class of CLC and COS data (see LUC legend in Fig. 2).

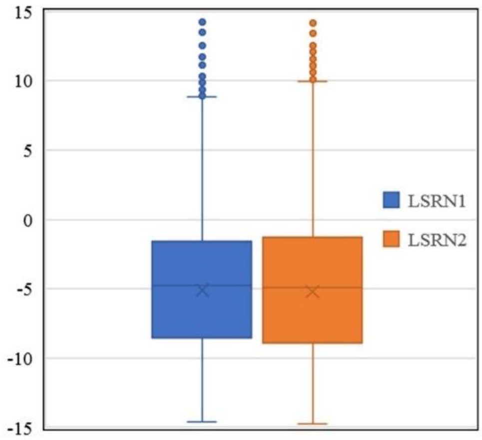

Figure 8. Landslide susceptibility of the road network. LSRN1 – IV assigned for LSM1; LSRN2 – IV assigned for LSM2.

ever, when a tabulation of the area of the road network used in this research and the LUC datasets was performed, the density of the roads was different in each LUC class between datasets (Fig. 7).

The IVs of LSM1 and LSM2 assigned to the road network differentiated the roads according to the landslide susceptibility, representing the highest IV where future landslides will occur and possibly rupture the road network or cause socioeconomic constraints due to total or partial blockages. In this case, the differences in the roads' landslide susceptibilities were also analyzed.

The IVs assigned to the road network do not have spatial agreement between the two models. The difference between the maximum and minimum IVs of the LSRN1 and LSRN2 variations is significant, with IV variation of approximately 1. The interquartile range of the IV is greater in LSRN2 than in LSRN1 (Fig. 8). However, the IV average is similar in LSRN2 in comparison to LSRN1.

The landslide susceptibility map of the road network obtained by LSM1 (resulting in LSRN1) (Fig. 9) shows that it is spatially contrasted along the road network, highlighting the places where future landslides that may cause disturbances on the roads are most likely to occur. Conversely, in the landslide susceptibility map of the road networks obtained by LSM2 (resulting in LSRN2), the IV assigned to the road network is generally lower when compared to LSRN1, a result derived from the LUC generalization (CLC) used in the input of model 2.

LSRN1 includes 14.1 % of the roads with a positive landslide susceptibility ($IV \geq 0$), and the roads with high landslide susceptibility ($IV > 10$) represent only 0.1 % of the total road network (Fig. 9). In LSRN2, the positive landslide susceptibility ($IV \geq 0$) increases (compared with LSRN1) and comprises 14.7 % of the total road network, where 0.1 % of this network corresponds to a high landslide susceptibility ($IV > 10$).

LSRN2 does not show a high variation in short road distances; i.e., the IV tends to be extended within each polygon of the same class of the CLC's LUC (larger polygons in comparison with the COS data), reducing the IV variation along the roads. The variation in the IV within each polygon of the LUC data is only explained by the remaining predisposing factors included in the model.

In LSRN2, the places with a high landslide susceptibility are not always identified as those where landslides effectively occurred (Fig. 10). The landslide susceptibility of the road network enhances the results obtained with COS (LSRN1) in areas with very high landslide susceptibility, precisely where landslides were validated in the fieldwork. These results show the importance of LUC data properties in the spatial differentiation of landslide susceptibility.

The spatial agreement and kappa coefficient between the LSRN1 and LSRN2 landslide susceptibility classes are 89.7 and 83.1 %, respectively (Table 5). In general, the individual susceptibility classes present a high agreement (≥ 80 %, except the high and very high classes of LSRN2) but with differences between the two models. For example, the landslide susceptibility class "very high" comprises 0.05 % and 0.06 % of the total road network in LSM1 and LSM2, respectively, but LSRN2 presents 20.4 % of the omission differences in the same susceptibility class compared to the 3.8 % commission differences of LSRN1. The intermediary susceptibility classes of the two models highlight the omission and commission differences.

Although variations exist between LSRN1 and LSRN2 landslide susceptibility, the relationship between the two models' outputs is high, presenting a Pearson correlation co-

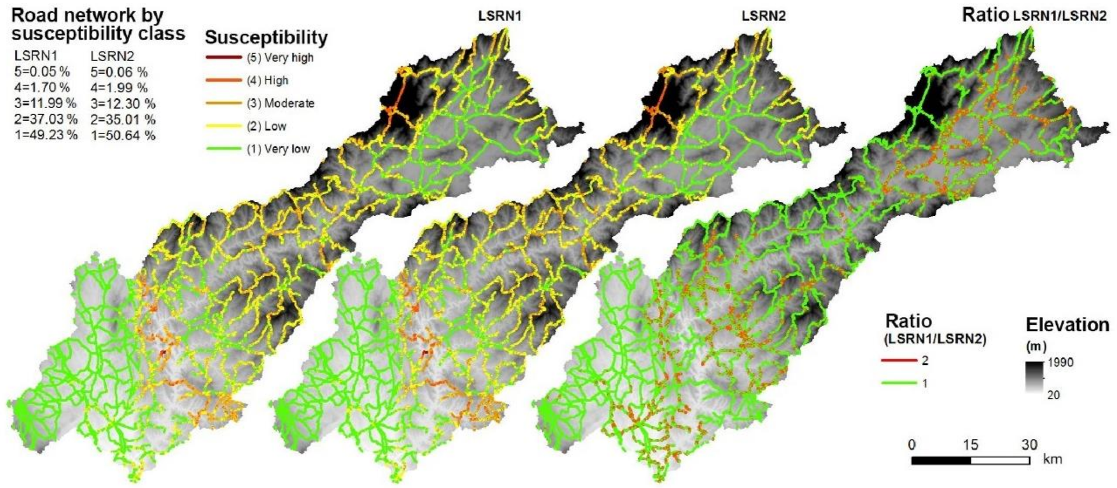

Figure 9. Landslide susceptibility of the road network (LSRN1 and LSRN2) and the ratio between landslide susceptibility classes of the roads. LSRN1 – IV assigned for the LSM1; LSRN2 – IV assigned for the LSM2.

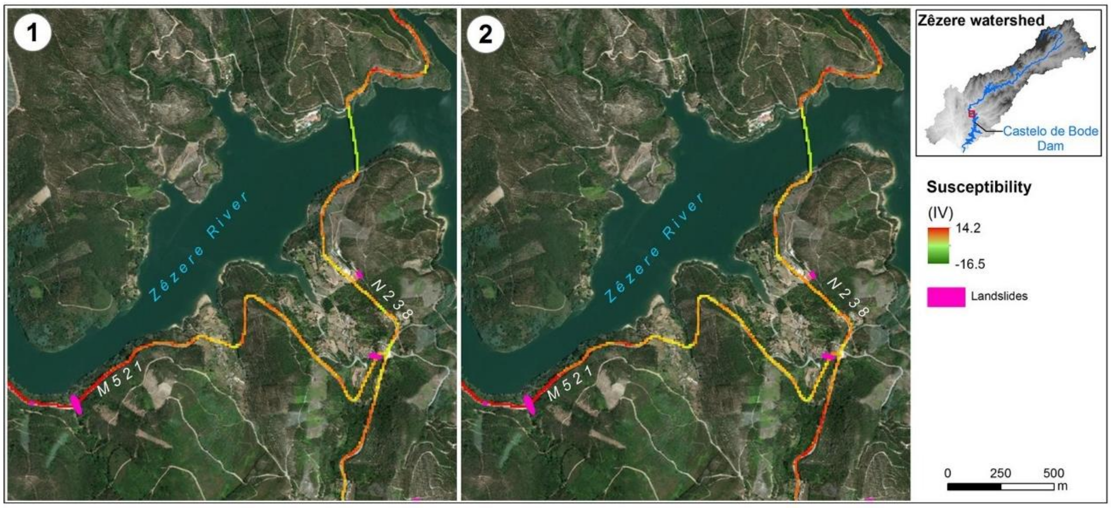

Figure 10. Examples of the landslide susceptibility of the road network in the Ferreira do Zêzere municipality. 1 – LSRN1; 2 – LSRN2.

efficient of 0.98 (significance level $p<0.05$). The results of this correlation reflect the existence of an agreement on the spatial variation between LSRN1 and LSRN2; i.e., in general, when the IV of one output increases the other also increases, or vice versa, regardless of the discrepancy among the IVs of the same cells of each output.

The LSRN1 and LSRN2 results were crossed with all landslides that caused perturbations or disruptions of the road network, and the performance of models was assessed. Overall, the results were very good, with 89.5 % and 89.3 % AUC for LSRN1 and LSRN2, respectively. However, LSRN1 offers slightly better results when compared to LSRN2, as can be seen in the representation of the SRC (Fig. 11); i.e., up to 20 % of the total area of the road network validates approximately 83 % of the landslide susceptibility of LSRN1 and LSRN2. Nevertheless, LSRN2 shows a slightly better performance (to approximately 45 % of the total area of the road network), but LSRN1 improves its validation performance at this point, being completely validated with 67 % of the to-

Table 5. Spatial agreement between LSRN1 and LSRN2 (percentage of road network).

	LSRN2							
LSRN1	Very low (IV < − 5)	Low (IV −5–0)	Moderate (IV 0–5)	High (IV 5–10)	Very high (IV > 10)	Total area (%)	Agreement (%)	Commission differ. (%)
Very low (IV < − 5)	46.3	2.2	0.0	0.0	0.0	48.5	95.5	4.5
Low (IV −5–0)	3.5	31.7	2.3	0.0	0.0	37.4	84.6	15.4
Moderate (IV 0–5)	0.0	1.7	10.1	0.5	0.0	12.3	82.4	17.6
High (IV 5–10)	0.0	0.0	0.2	1.5	0.01	1.7	88.1	11.9
Very high (IV > 10)	0.0	0.0	0.0	0.0	0.05	0.05	96.2	3.8
Total area (%)	49.8	35.5	12.58	2.03	0.06			
Agreement (%)	93.0	89.2	80.3	75.0	79.6	Overall agreement: 89.7 %		
Omission differ. (%)	7.0	10.8	19.7	25.0	20.4	Kappa coefficient: 83.1 %		

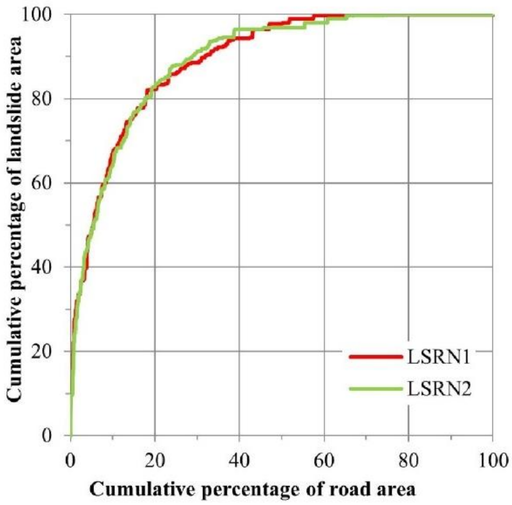

Figure 11. Success rate curves of LSRN1 and LSRN2 models.

tal area of the road network, while LSRN2 is validated with 74 % of its area.

4 Discussion

In landslide hazard and risk assessment, the LUC data integrate the controlling factor group and, in many evaluations, are directed by another factor input to the model. Usually LUC data are used as a landslide conditioning factor, which, in some cases, is scarce, generalized, and not very detailed. For example, Eeckhaut and Hervás (2012) verified that in different locations of Europe CLC is widely used for landslide assessment because it is the only LUC data available. Remote sensing and satellite images contributed to LUC data acquisition for landslide susceptibility assessment in different times (Guzzetti et al., 2012) and territories and minimize some problems of scarcity and detail (thematic and resolution). LUC is an important conditioning factor in landslide susceptibility (Pisano et al., 2017), and the high accountability index results prove this fact (Table 4).

There are several studies about the influence of land use cover changes on landslide susceptibility (e.g., Karsli et al., 2009; Mugagga et al., 2012; Promper et al., 2014; Reichenbach et al., 2014), although to the best of our knowledge there are no approaches that analyze the influence of different LUC datasets with different properties (date and base maps used on the production, spatial resolution, scale, minimum mapping unit, or others) on the landslide susceptibility results. When the landslide predisposing factors are collected, the LUC dataset must be selected according to its abovementioned properties and not only on the basis of its availability and free-of-charge conditions.

When different LUC datasets are available, the choice for the LUC dataset used in the landslide susceptibility assessment is not always clearly justified, and the results may vary according to LUC data properties selected. For Portugal different LUC datasets (with different properties) are available, but the use of each dataset can generate different conclusions; for example, different land use and land cover changes in the same period were observed by Meneses et al. (2018c).

This study highlights the landslide susceptibility differences derived exclusively from the LUC data properties because the other predisposing factor maps are the same in both models. Although if another method is used or the terrain mapping unit or another characteristic is changed, the results may vary, which has already been widely discussed (Chen et al., 2016; Den Eeckhaut et al., 2010; Guzzetti et al., 2006; Oliveira et al., 2015a; Zêzere et al., 2017).

Further, the data of soil and lithology were constrained and very generalized (1 : 1 000 000 and 1 : 50 000 scales, respectively), and this factor can influence the IV results if more detailed data were considered in the modeling process. The performance of the landslide susceptibility mapping and assessment is controlled by the quality of the available data not only the method (Pourghasemi et al., 2014).

Some research works refer to the quality of geoinformation (scale and precision) on the final result changes (e.g., Etter et al., 2006). In this case, the degree of completeness and the positional, geometric, and thematic agreement of the selected LUC data were evaluated by different proprietary institutions, with more than 80 % accuracy, i.e., where the semantic inconsistency error was reduced, an important factor in reducing the error propagation and achieving a product with the best quality (Van Oort and Bregt, 2005; Regnauld, 2015).

The landslide inventory was obtained by photointerpretation, which is certainly not complete, especially in forest and agricultural areas, a fact that could have an impact on the landslide susceptibility zonation of the study area. This inventorying method does not allow for shallow or small landslide identification in forest areas, where the type, height, and density of the vegetation is important to landslide activity (Guzzetti et al., 2012), or in cultivated areas where agricultural practices erase the morphological and LUC signature of slope failures (Fiorucci et al., 2011). The quality and completeness of the landslide inventories can interfere with the quality of future landslide spatial occurrences (Galli et al., 2008; Guzzetti et al., 2012; Reichenbach et al., 2018). However, the landslide inventory is the same for both landslide models presented in this research, and the variation results depend exclusively on the LUC datasets that are integrated into each model.

The correlation between the outputs of each model is high, but there are spatial differences between them. The COS data are more detailed (1 : 25 000) than the CLC data (1 : 100 000), and the LUC classes are more differentiated in the territory, allowing greater detail and agreement in determining the areas with high landslide susceptibility, which were verified in LMS1. In model 2, CLC data are less detailed and contribute to IVs that are lower (low and very low landslide susceptibility in LSM2) compared with LSM1.

IV is more generalized along the road network at LSRN2 when compared with LSRN1, results derived exclusively from the input of LUC data with different properties in the models. These results highlight the importance of generalization and scale of LUC data selected in the landslide susceptibility assessment.

In the road network intersection with the LUC data, a high absence of road data was observed in the class industrial, commercial, and transport units, which is explained by the cartographic generalization due to the minimum mapping unit and minimum distance among lines of each LUC dataset. These factors exclude the road data due to the minimum requirements defined in the technical specifications of each LUC dataset creation. However, the distribution of the road network among the LUC classes is quite variable in both LUC datasets (COS and CLC), one of the factors that also justifies the variation in landslide susceptibility observed in different outputs.

The results of the PRC and AUC for LSM1 and LSM2 show a high quality and performance of both models in the landslide susceptibility area determination (Guzzetti et al., 2006), but LSM1 presents a slightly better performance. Nevertheless, the prediction landslide results were validated with the landslide test group and present good results to be assigned in the road network.

The LSRN1 and LSRN2 models' validation results demonstrate that the models effectively identify the places where the landslides occurred and are more likely to occur in the future. In this case, the SRC and AUC note the high efficiency of the models (Guzzetti et al., 2006), with LSRN1 having a slightly higher efficiency, highlighting the properties of the LUC data.

Some roads in the study area were affected by landslides, a fact confirmed during the fieldwork developed to validate the landslide inventory (examples of some road blockage or damage in the Serra da Estrela and sample areas). In certain cases, the affected roads are important accesses points for the most isolated villages in the study area, and, in some cases, a landslide can isolate the villages because part of the affected infrastructure is the only public access, a fact verified in the sample areas.

The results highlight the importance of LUC data properties in landside assessment. More detailed LUC data (COS data) allow better landslide susceptibility results, a fact that was also described by Dymond et al. (2006), identifying some places where landslides occurred in the study area. Detailed predisposing factor data are recommended in landslide susceptibility assessment, a fact also mentioned in other studies. For example, Fressard et al. (2014) refer to the importance of detail in geomorphological variables to obtain high-quality results in landslide prediction.

This study was performed in a specific watershed, which highlights that landslide susceptibility changes according to the LUC data properties. It is recommended that the LUC data to be used as a predisposing factor of landslide susceptibility (e.g., in road networks) be as detailed as possible and small-scale LUC datasets be avoided ($\geq$ 25 000). Further research is needed to test if these results change when the scale is different (e.g., national scale or very detailed scale).

In the analysis of the risk associated with road transportation, the higher the probability of a given event or incident, the greater the consequences (Berdica, 2002). In this context, the determination of the locales with the highest landslide susceptibility is very important, enabling prevention and minimizing these consequences or enabling better reactions when dealing with emergencies because road closures change the travel and reaction time (Meneses and Zêzere, 2012).

5 Conclusions

Landslide susceptibility in the Zêzere watershed is spatially variable, highlighting some characteristics of the study area's geo-factors in high landslide density in a specific location, for example, the highest slope angles and certain LUC types (e.g., forests and scrubland) and lithology.

The properties of the data that are integrated into the landslide susceptibility models are also an important issue to be considered since the variation in the properties of the same geo-factor provided different results, in this case LUC with different properties.

More detailed LUC data (COS) allow better landslide susceptibility results, while more generalized LUC data (CLC) resulted in the landslide susceptibility being more reduced, disallowing the identification of some places where landslides occurred. However, the results of the two susceptibility models showed good performance, a fact demonstrated by the validation of the models' results.

The assignment of the landslide susceptibility results to the road network allowed the identification of the locations with the highest spatial probability for landslide occurrence. The LSRN1 map stands out with better results due to the integration of the COS dataset, showing the importance of LUC data detail in the identification of locations where landslides have occurred. The LSRN2 map does not have good performance in the identification of high landslide susceptibility in all road sections where landslides have occurred. In general, both LSRN1 and LSRN2 show the same trend in the spatial variation in landslide susceptibility of the study area's road network, highlighting the high susceptibility on the slopes of the Serra da Estrela and near the Castelo de Bode reservoir.

Finally, LUC data properties were shown to be important in the variation in landslide susceptibility results. When the locations where landslides are likely to occur are known, alternative options can be created to avoid partial or complete isolation of certain localities, reduce the social and economic constraints of this population, and adopt preventive measures and alternative evacuation paths in case of landslide occurrence.

Data availability. The data used in this paper are accessible at http://www.dgterritorio.pt/, https://land.copernicus.eu/pan-european/corine-land-cover (LUC), https://sniamb.apambiente.pt/ (soil and llithology), and https://www.igeoe.pt (road network). All websites were last accessed on 10 June 2017.

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Capítulo 3

ALTERAÇÕES DE USO E OCUPAÇÃO DO SOLO EM PORTUGAL CONTINENTAL: ABORDAGEM MULTIESCALA E MULTITEMPORAL E RESPETIVAS FORÇAS MOTRIZES

3.1. INTRODUÇÃO

As transições de UOS observadas nas últimas duas décadas em Portugal continental foram bastante significativas, sobressaindo a transição de área florestal para outros tipos de UOS. Vários trabalhos sobre esta temática foram desenvolvidos neste território (e.g., Cabral *et al.*, 2014; DGT, 2014; IGP, 2010; Meneses *et al.*, 2014; Meneses *et al.*, 2013; Nunes, 2007; Ribeiro *et al.*, 2014; Vale *et al.*, 2014), mas é necessário compreender os diversos resultados apresentados nestes estudos, visto que são utilizadas diferentes metodologias e diferentes conjuntos de geoinformação na modelação e análise das AUOS.

O artigo Meneses *et al.* (2018b) (apresentado na secção 3.2) sintetiza os resultados de uma abordagem inovadora, desenvolvida com cartografia de UOS recente do território português (CLC, a mais recente à data de publicação do artigo), informação que se revela fundamental para estudar detalhadamente as alterações de UOS ao longo do tempo. Os resultados apresentados neste artigo contribuem para analisar e perceber as AUOS (de 1990 a 2012) utilizando a cartografia CLC de Portugal continental (cobertura integral), mas também um conhecimento inovador que ajuda a perceber as dinâmicas do UOS. Foram analisadas as tendências de variação espacial dos vários tipos de UOS, observando-se a partir destas análises que esta variação não é constante ao longo do tempo. Esta análise é fundamental para demonstrar a existência de diferentes dinâmicas espaciais e temporais das AUOS no território em análise, que requerem um estudo mais aprofundado. De uma forma geral, os resultados obtidos neste artigo evidenciam a redução de área florestal e de área de determinados tipos de ocupação e uso agrícola, destacando-se paralelamente o aumento das áreas urbanizadas. Refere-se no entanto que as variações observadas em termos globais assumem diferentes dinâmicas quando analisadas a nível regional (NUTS II), ilustrando este facto a existência de diferentes forças motrizes associadas a cada região, conforme referido por Meneses *et al.* (2017). No entanto, é fundamental determinar as tendências futuras das AUOS, pois essa determinação permitirá formalizar políticas e ações que visem atenuar ou eliminar impactos negativos resultantes das AUOS aqui apresentadas.

No artigo Meneses *et al.* (2018b) apresentam-se algumas alterações futuras de UOS estimadas com recurso a autómatos celulares (CA-Markov). Os resultados obtidos revelaram a tendência para o aumento e redução dos tipos de UOS anteriormente referidos de modo indiferenciado. Destaca-se nestas projeções das AOUS o aumento de área ocupada por matos na macro classe "floresta", sendo este resultado o culminar da devastação que a floresta portuguesa sofreu ao longo das últimas décadas, quer induzida pelo Homem, para as suas atividades agrícolas, florestais e para a artificialização, quer pelos incêndios florestais, eventos cada vez mais catastróficos (registo de perda de muitas vidas humanas e avultados prejuízos materiais nos últimos anos) e cada vez com maior extensão de área ardida.

Para perceber a relevância de internalizar a qualidade da geoinformação na avaliação das AUOS, a área de UOS obtida pelas classes da CLC foi comparada com outra cartografia de UOS, nomeadamente a COS (cartografia com diferentes propriedades). Esta comparação ilustra discrepâncias de área significativas em algumas classes de UOS. Por sua vez, estas discrepâncias podem justificar também diferentes conclusões sobre as AUOS, i.e., os resultados de projeções de AUOS obtidos com a CLC podem ser significativamente diferentes dos obtidos com a COS.

Quanto às análises da variação temporal de área por cada tipo de UOS apresentadas no artigo Meneses *et al.* (2018b), em virtude da disponibilização recente da versão CLC para o ano 2018 (disponibilizada após a publicação deste artigo), fez-se a atualização dos resultados apresentados ao nível das NUTS II, nomeadamente a área total por cada classe nos diferentes anos disponíveis (Figura 2.1). Considerando a integração da informação da CLC 2018 verificou-se, relativamente aos dados da CLC 2012, um aumento generalizado (valores absolutos) dos espaços florestais degradados, cortes e novas plantações por todas as NUTS, mas destaca-se também o aumento de área ocupada por matos nas NUTS Norte e Centro, enquanto no Alentejo sobressai o aumento de área dedicada aos sistemas agroflorestais e pastagens, com elevada redução de culturas anuais de sequeiro, mas com um ligeiro aumento de culturas anuais de regadio.

As florestas de resinosas apresentaram redução drástica de área na NUTS II Centro, sendo esta redução explicada essencialmente pela extensão dos incêndios florestais que ocorreram antes de 2018. Porém, as áreas ardidas nesta NUTS embora apresentem um ligeiro aumento, não refletem a elevada redução de área florestal, pois grande parte das áreas afetadas por estes eventos foi integrada nas classes "Espaços florestais degradados, cortes e novas plantações" e "Matos" da geoinformação CLC. Neste sentido, caso se pretenda analisar as áreas ardidas somente com base na CLC, os resultados a obter não irão refletir a realidade sobre as áreas afetadas por estes eventos, evidenciando-se assim a importância da análise das propriedades da geoinformação. Esta discussão apresenta-se mais detalhada no Capítulo 4.

Embora a cartografia CLC seja disponibilizada por entidade oficial (AEA), verificou-se que no caso da CLC 2018 há erros grosseiros na classificação dos olivais na região do Algarve, evidenciando-se estes no aumento relativo de área exagerada entre 2012-2018 (Figura 2.2).

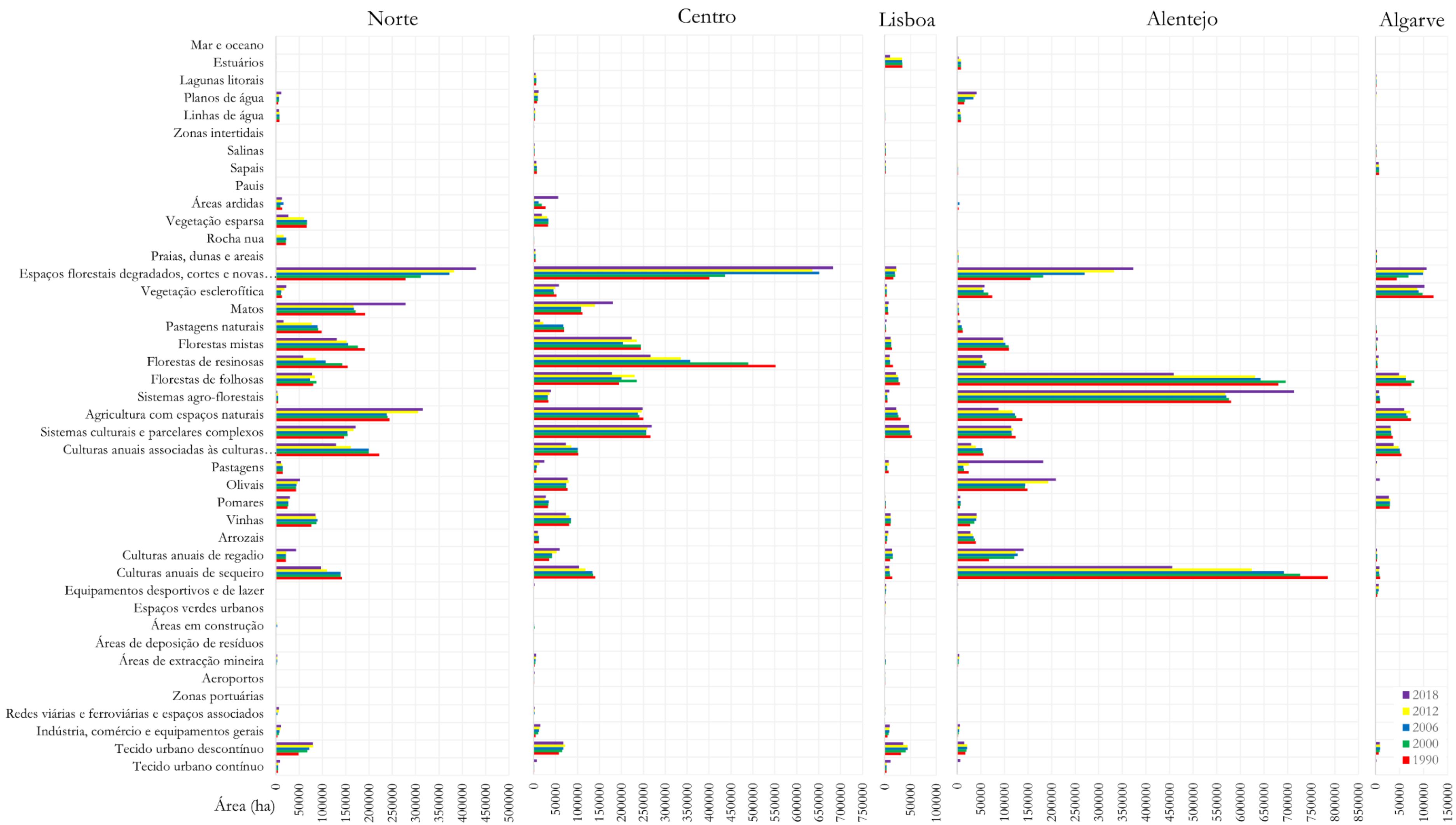

Figura 2.1. Uso e ocupação do solo por NUTS II de Portugal continental (dados da CLC, nível 3).

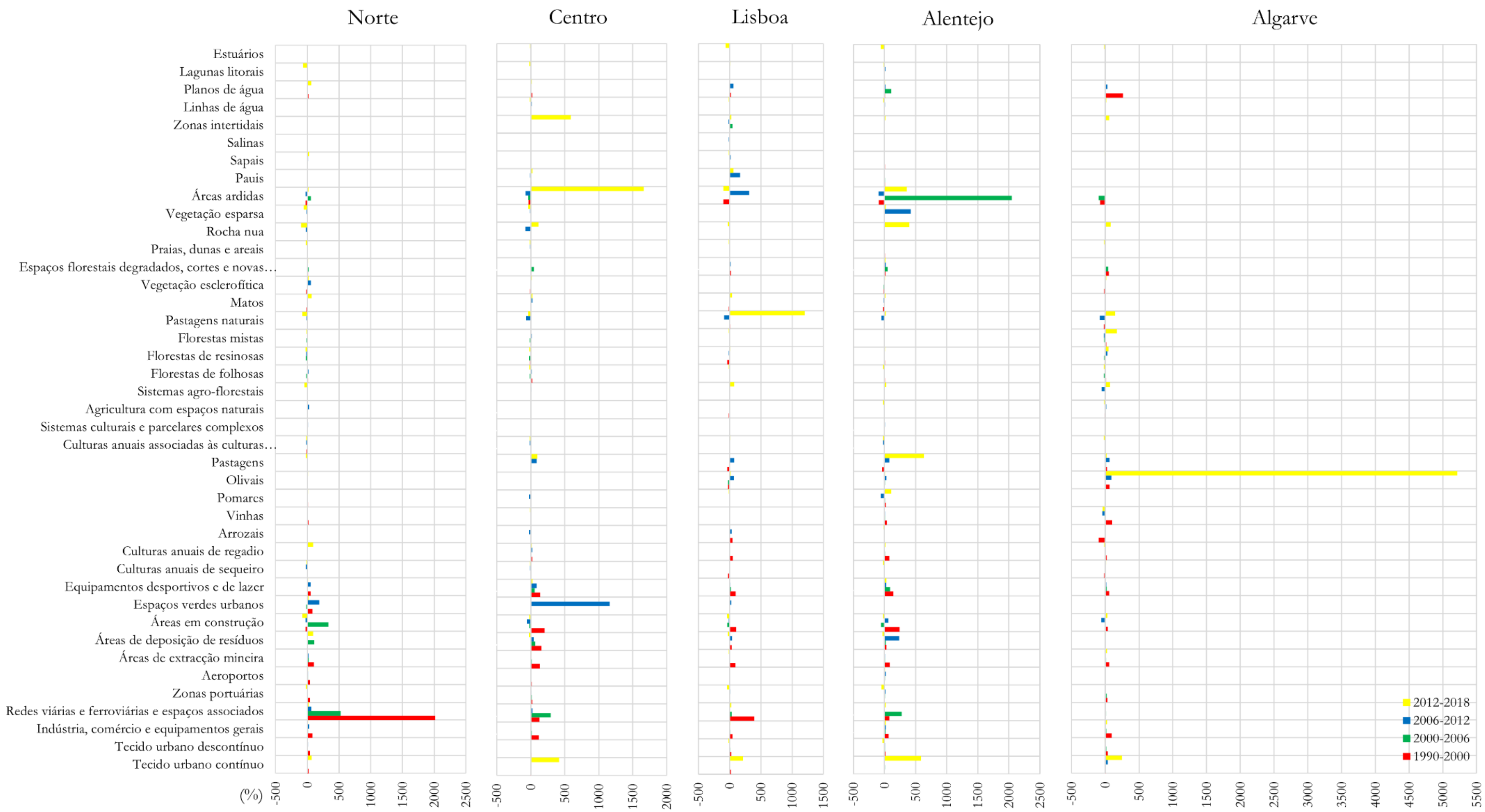

Figura 2.2. Variação relativa de área por tipo de uso e ocupação do solo nas NUTS II de Portugal continental (dados da CLC, nível 3).

Na Figura 2.3 apresentam-se alguns exemplos de classificações erradas de olival na região do Algarve. Este é apenas um exemplo de discrepância de área encontrada para um determinado tipo de UOS entre dois momentos, que resultou essencialmente de problemas de classificação, i.e., a qualidade da geoinformação não apresenta elevado rigor, nomeadamente nesta região, com problemas sobretudo na validação temática. Neste sentido, é exigido aos utilizadores uma tarefa adicional na verificação da qualidade da geoinformação do UOS, para que os resultados a obter a partir da mesma não apresentem incongruências derivadas essencialmente dos problemas de ordem técnica, como os referidos anteriormente.

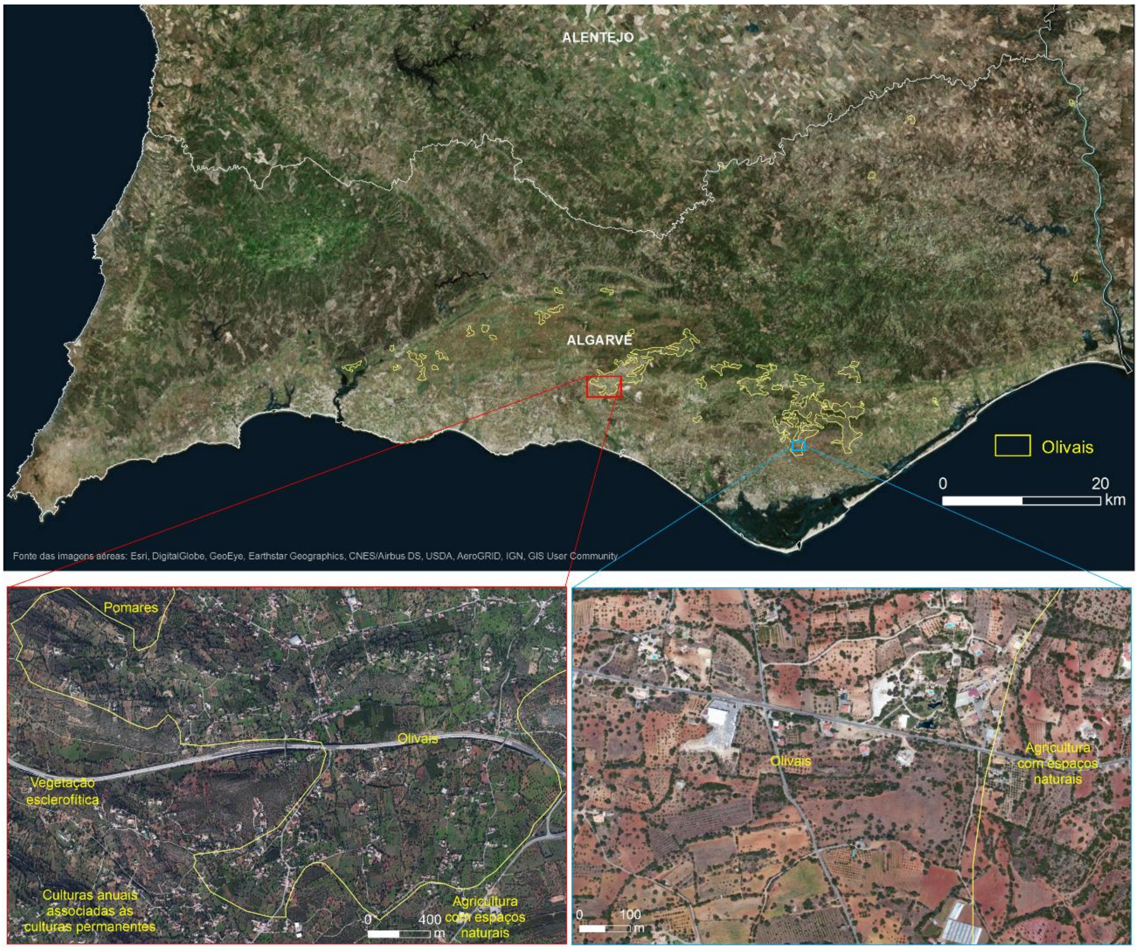

Figura 2.3. Exemplos de classificação de olival errada na região do Algarve (dados da CLC 2018, nível 3).

Contudo, os resultados das diversas avaliações apresentadas neste capítulo são importantes para se compreender as AUOS no caso português, para o planeamento do território num futuro próximo, mas também são relevantes para melhorar a qualidade de produção de geoinformação de UOS, adequando a revisão e controlo de qualidade às necessidades dos principais grupos de utilizadores.

Identificar as forças motrizes que deram origem a determinadas AUOS tornou-se importante para se adotarem medidas ou estratégias de ordenamento do território, bem como na gestão de recursos naturais. Esta temática tem sido abordada globalmente em diferentes contextos (diferentes territórios) e tem adquirido maior ênfase nos anos mais recentes (Armenteras *et al.*, 2019; Betru *et al.*, 2019; Kleemann *et al.*, 2017; Kogo *et al.*, 2019; Magesh e Chandrasekar, 2017; Quintero-Gallego *et al.*, 2018; Shi *et al.*, 2017).

No caso português também foram analisadas algumas forças motrizes para as AUOS que ocorreram entre 1995 e 2010 em Portugal continental (artigo da secção 3.3 e respetivo material suplementar do anexo 3) e também algumas implicações associadas a estas AUOS (Meneses *et al.*, 2017).

De uma forma geral, as AUOS em Portugal continental foram bastante acentuadas nas últimas duas décadas, onde se evidencia o aumento da artificialização do solo em termos relativos. Face às múltiplas consequências que o aumento da artificialização do solo pode originar (degradação do solo, destruição de floresta, ocupação de solos férteis para agricultura, entre outros), é premente perceber como este processo pode variar ao longo do território e quais as consequências que daí podem advir.

A artificialização do solo, seja para a construção de infraestruturas de habitação, de comércio, de indústrias, seja para infraestruturas rodoviárias, entre outras, tem na sua base múltiplos fatores, por um lado, os ambientais que podem ser considerados condicionantes (litologia, tipo de solo, declive das vertentes, reservas naturais, entre outros), por outro, os socioeconómicos (disponibilidade financeira para a infraestruturação, crescimento da população, expansão da rede de transportes, etc.).

O artigo Meneses *et al.* (2016a) (secção 3.4) apresenta a avaliação da probabilidade da artificialização dos solos na bacia hidrográfica do Rio Zêzere, usando um conjunto de geoinformação biofísica e dois modelos diferenciados: o Valor Informativo e a Lógica Fuzzy (operador Gamma). Nesta investigação, ao utilizar-se apenas o conjunto de geoinformação anteriormente referido, teve-se por base o conceito de Uniformitarismo, i.e., as próximas áreas artificializadas provavelmente irão surgir em áreas sob as mesmas condições biofísicas/naturais em que a artificialização ocorreu no passado. Por exemplo, a artificialização do solo na bacia hidrográfica em referência ocorreu sobretudo em áreas com fraco declive, sendo aqui o declive considerado uma variável importante para identificar áreas condicionantes à expansão urbana, sobretudo para vertentes com elevado declive, ou então, serão necessárias medidas de regularização e estabilização para que se possa construir, o que carece de grandes investimentos financeiros. Por outro lado, por se tratar de uma bacia localizada numa área essencialmente rural, muitos dos solos são utilizados para fins agrícolas e florestais, onde fatores como a precipitação, humidade, insolação, ensombramento das vertentes, tipo de solo, etc., também podem explicar a construção de determinadas infraestruturas de forma dispersa (e.g., habitações rurais, instalações de pequenas indústrias, ou mesmo estradas). A modelação da probabilidade de artificialização do solo efetuada compreendeu diversas variáveis ambientais, utilizando-se como base as áreas artificializadas representadas na CLC de 1990 (variável dependente). Como existem versões da CLC posteriores à utilizada na modelação, foi possível validar os resultados obtidos cruzando com as novas áreas artificializadas que surgiram até 2012, através da CLC 2012. Também se verificou nesta investigação a elevada eficiência dos modelos utilizados na determinação de áreas com maior probabilidade de virem a ser artificializadas. Estes resultados também configuram uma ferramenta útil para o ordenamento do território.

Convém ter em atenção que os resultados apresentados neste último artigo foram obtidos apenas com base num conjunto de geoinformação biofísica, mas tratando-se de artificialização do solo, i.e., um tipo de UOS resultante apenas de intervenção antrópica, qualquer área com reduzida probabilidade de artificialização apresentada pode ser convertida a qualquer momento, pois o Homem, através das múltiplas possibilidades de engenharia disponíveis, tem a capacidade de modificar o território em qualquer momento, mesmo em áreas com elevado declive que aqui se apresentam com reduzida probabilidade de artificialização.

3.2. Artigo - Meneses, B.M.; Reis, E.; Vale, M.J.; Reis, R. (2018b) - Modeling land use and land cover changes in Portugal: a multi-scale and multi-temporal approach. Finisterra, LIII (107), pp. 3-26.

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Artigo

MODELLING LAND USE AND LAND COVER CHANGES IN PORTUGAL: A MULTI-SCALE AND MULTI-TEMPORAL APPROACH

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ABSTRACT – Portuguese territory has experienced relevant land use and land cover changes (LUCC) in recent decades. The revision of existing land use and land cover (LUC) datasets and the production of new datasets have allowed us to better understand LUCC over time. This study furthers that analysis by using the most recent LUC datasets, which cover the entirety of the Portuguese continental area from 1990 to 2012 and presents innovative knowledge that aids in the understanding of LUC dynamics within that period. This study shows that the trends that have induced spatial variations within different LUC classes have changed over time, revealing different spatial and temporal dynamics of those LUCC in the Portuguese territory. The main LUCC are related to reductions in forests and certain types of agricultural areas and increases in urban areas, but the main LUCC assume different dynamics when taken at the regional scale (NUTS II). Future tendencies of LUCC were also estimated using Cellular Automata-Markov (CA-Markov), and the results show the increasing and decreasing tendencies of the LUC types previously mentioned. The areas of LUC datasets with different properties were compared, and large area discrepancies were observed for some LUC classes. These assessments provide relevant results for the evaluation and understanding of LUCC for Portuguese planning processes in the near future.

Keywords: Land use and land cover (LUC); LUC geoinformation properties; LUC changes (LUCC); LUCC projection; mainland Portugal.

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4 Meneses, B. M., Reis, E., Vale, M. J., & Reis, R. *Rev. Finis. LIII*(107), 2018, pp. 3-26

RESUMO – MODELAÇÃO DAS ALTERAÇÕES DE USO E OCUPAÇÃO DO SOLO EM PORTUGAL. UMA ABORDAGEM MULTIESCALA E MULTITEMPORAL. Em Portugal ocorreram grandes transições de Uso e Ocupação do Solo (UOS) nas últimas duas décadas. A revisão da cartografia de UOS e a produção de nova cartografia vem permitir o estudo das alterações de UOS ao longo do tempo. Este estudo apresenta avanços na análise destas alterações (de 1990 a 2012) utilizando a cartografia mais recente para o território português (cobertura integral), mas também um conhecimento inovador que ajuda a perceber essas alterações. As tendências de variação espacial dos vários tipos de UOS não são constantes ao longo do tempo, revelando as diferentes dinâmicas espaciais e temporais destas alterações no território em análise. Sobressai a redução de área florestal e de determinados tipos de áreas agrícolas, e o aumento das áreas urbanas. No entanto, as variações observadas assumem diferentes dinâmicas a nível regional (NUTS II). As futuras alterações de UOS foram estimadas através de autómatos celulares (CA-Markov), revelando os resultados tendência para o aumento e redução dos tipos de UOS anteriormente referidos. A área de UOS foi comparada com outra cartografia de UOS (com diferentes propriedades), observando-se grande discrepância de área em algumas classes de UOS. Estas avaliações são importantes para se compreender as alterações de uso e ocupação do solo relevantes para o planeamento do território em Portugal num futuro próximo.

Palavras-chave: Uso e ocupação do solo (UOS); propriedades da geoinformação de UOS; alterações UOS; projeções de UOS; Portugal Continental.

RÉSUMÉ – LES TYPES D'UTILISATION ET D'OCCUPATION DO SOL AU PORTUGAL. UNE MÉTHODOLOGIE MULTI-SCALAIRE ETMULTI-TEMPORALE. Au cours des deux dernières décennies, le Portugal a enregistré de grands changements dans l'utilisation et l'occupation du sol (UOS). La révision des données existantes et la production de données nouvelles permettent de mieux comprendre les changements subis par l'UOS. On utilise ici des données allant de 1990 à 2012. Elles permettent non seulement de cartographier tout le territoire mais montrent aussi des aspects nouveaux, car la tendance de variation des divers types d'utilisation du sol s'est modifiée dans le temps. On note surtout la réduction de l'aire forestière et de certains types agricoles, et l'amplification des aires urbaines. Mais ces variations ont des dynamiques régionales (NUTS II) différenciées. Pour évaluer les futures tendances de l'UOS, on a utilisé des automates cellulaires (CA-Markov). On constate ainsi des différences importantes, qu'on a comparées avec les résultats obtenus par d'autres méthodes cartographiques. Les résultats seront à prendre en compte dans les processus de planification du territoire qui seront mises prochainement en œuvre.

Mots clés: Utilisation et occupation du sol (UOS); Propriété de la Géo-information de l'UOS; Changements de l'UOS; Projection de l'UOS; Portugal Continental.

I. INTRODUCTION

1. Land use and land cover

The study of the evolution of land use and land cover (LUC) has been of general concern in many territories due to observed transitions that reflect spatiotemporal dynamics (Shi, Chen, & Pan, 2000; Nunes, Serra, Pons, & Saurí, 2008; Almeida, & Coelho, 2011; König *et al.*, 2013). In these approaches, the factors at the origin of the largest land use and land cover changes (LUCC) are the most important for the observed negative impacts (e.g., water erosion due to forest losses, catastrophic phenomena such as floods that are related to increases in impermeable surfaces, and reductions in surface water quality) (Fearnside, 1995; Hansen, Stehman, & Potapov, 2010; Schoene & Bernier, 2012).

Studies of LUCC are essential to the understanding of many presently observed phenomena, especially climate changes (Li *et al.*, 2017; Tasser, Leitinger, & Tappeiner, 2017), biological (Moreira *et al.*, 2012; Song & Deng, 2017) and environmental perturbations (Kim *et al.*, 2017), landscape fragmentation (Nurwanda, Zain, & Rustiadi, 2016), human health impacts (Patz & Olson, 2017) and the growth of urban areas (Du & Huang, 2017), among others.

LUC in Portugal has also suffered major changes over the past few decades. Those changes can be retrieved and documented through the analysis of the country's diverse thematic cartography, thereby documenting the past (Meneses, Saraiva, Reis, & Vale, 2014; Meneses, Vale, & Reis, 2014). Other LUCC studies on the Portuguese territory have been developed by other authors in past years. For example: Moreira *et al.* (2012) evaluated the impacts of LUCC on the biodiversity of agricultural landscapes in four Alentejo regions; Freire, Santos and Tenedório (2009) studied recent urbanization and LUCC in Portugal, emphasizing the influence of coastlines and coastal urban centres; and Abrantes, Fontes, Gomes and Rocha (2016) studied the compliance of land cover changes with municipal land use planning in the Lisbon region.

With the latest LUC cartography (full coverage), it will be possible to obtain new and more accurate results for the Portuguese territory. The comparison and analysis of this cartography with older cartography is crucial for understanding LUCC dynamics (Pôças, Cunha, Marcal, & Pereira, 2011; Teixeira, Teixeira, & Marques, 2014) and will allow comparisons of different spatio-temporal LUCC realities. The Corine Land Cover (CLC) cartography, which was recently produced for 2012 and is available from the European Environment Agency (EEA), allows this type of analysis of LUC evolution for a longer period (1990-2012). Since the criteria and specifications remained constant over this period, the analysis of LUC evolution can be consistently and systematically undertaken, allowing analyses at a detailed level.

The LUCC for Portugal were analysed in the Landyn research project for 1980, 1995 and 2010, based on a sampling methodology that used 1279 LUC samples (the area for each sample was 4 km^2). In that project, the areas occupied by 32 classes of LUC in mainland Portugal were estimated for the above years through the extrapolation of sample observations (DGT, 2013b; Meneses, Vale, *et al.*, 2014).

Based on the estimated areas, LUCC in Portugal were evaluated. The results showed large area variations between each type of LUC (emphasizing reductions in agricultural land), which allowed us to perceive some transition dynamics (Meneses *et al.*, 2014; Vale, Reis, & Meneses, 2014).

Other studies have been undertaken in this territory using LUC geoinformation. For example, the work used to support the reporting of emissions and carbon sequestration in the land-use sector (and respective changes) within the framework of the Kyoto Protocol (DGT, 2014) was based on LUC cartography (consisting of 19 classes) as a result of a Land Cover Mapping program (COS) in Portugal covering the years 1995, 2007 and 2010 that was prepared by the General Directorate for Territorial Development (DGT).

The driving forces and some implications arising from LUCC in this territory have been analysed. We highlight the expansion of agricultural land resulting from the construction of dams (Alentejo region) or the conversion of coniferous woods to eucalyptus woods associated with the trend towards increased gross value added and employment in industry and forestry (Meneses, Reis, Pereira, Vale, & Reis, 2017).

The methodologies used in the evaluations of LUCC are essentially based on transitions between various times using dynamic or transition tables (Shi *et al.*, 2000; Yu, Zang, Wu, Liu, & Na, 2011). LUCC modelling is typically performed using LUC themes transformed into raster data. This process can lead to deviations in the results derived from the resulting generalizations from the conversion process of the initial geoinformation (vector data). These deviations can be even more expressive when country-level modulation is undertaken, as in mainland Portugal (approximately 89,000 km^2).

Available geoinformation with certain properties is used for LUCC modelling, and as a result will give specific results, but these will vary if we use different datasets with different properties. In this sense, it is necessary to understand the influence of geoinformation properties on the results and also to avoid or at least to minimize errors, especially propagation errors (Veregin & Hargitai, 1995; Howard Veregin, 1998; Duckham, Mason, Stell, & Worboys, 2001).

Many LUCC models are available for evaluating LUCC. For example, the EROS team (USGS) developed the FOREcasting SCEnarios of Land-use Change (FORE-SCE) modelling framework to provide spatially explicit projections of future LUCC, and that model was used to produce LULC scenarios for part of the U.S. (Sohl *et al.*, 2014; Sohl, Wimberly, Radeloff, Theobald, & Sleeter, 2016). The MaxEnt model has also been used for the multi-temporal modelling of LUCC (Amici, Marcantonio, La Porta, & Rocchini, 2017), among other uses. On the other hand, software packages for LUCC modelling have appeared, especially for projecting LUCC. We highlight the following: CLUE-S, DINAMICA EGO, Cellular Automata-Markov (CA-Markov) and Land Change Modeler (both available in IDRISI) (Mas, Kolb, Paegelow, Camacho Olmedo, & Houet, 2014). CA-Markov has been used in many studies of LUCC and provides good results (Myint & Wang, 2006; Kamusoko, Aniya, Adi, & Manjoro, 2009; Memarian *et al.*, 2012; Chen, Yu, & Zhang, 2013; Shafizadeh-Moghadam & Helbich, 2013; Sayemuzzaman & Jha, 2014; Aburas, Ho, Ramli, & Ash'aari, 2017; Ghosh *et al.*, 2017).

This study presents an innovative LUCC framework for mainland Portugal (past and future) and compares the results obtained by LUC datasets with different properties.

2. Objectives

The main objectives of this research are to analyse LUCC in Portugal over different periods (1990-2000, 2000-06 and 2006-12) using cartography that provides full coverage of the territory (CLC) and to analyse LUCC at the regional level. The secondary objectives are to assess the dynamics and LUCC and to determine future LUCC using cellular automata (CA-Markov). These results integrate the validation process, that is, the comparison of the expected LUC vs. published and validated LUC. The third objective is the comparison of the LUC obtained using CLC and COS, in order to evaluate the discrepancies between LUC datasets with different properties.

II. STUDY AREA, DATA, AND METHODS

The study area employed in this research was mainland Portugal (88,962.50 km^2). This territory is divided into five NUTS II units: North (23.8% of the area), Centre (31.6%), Lisbon (3.6%), Alentejo (35.4%) and Algarve (5.6%).

To determine the LUCC, CLC cartography for several years (1990, 2000, 2006 and 2012) was used; the maps are available on the European Environment Agency (EEA) and DGT websites.

To assess the dynamics of changes between the various types of LUC, i.e., to determine whether there have been area losses or gains in certain LUC types when comparing the beginnings and ends of each period, transition tables were computed using the CLC data for different years (1990 and 2012). These data (vector format) were analysed using the ArcGIS 10.3 software platform, which allowed the identification of the areas where changes occurred and those where the LUC did not suffer modifications. Subsequently, all of the results obtained using GIS (geographic information systems) were exported to alphanumeric databases to allow calculations of the areal changes and their statistical analysis.

To analyse the LUC at the regional level, we used LUC disaggregated at the third level (that is, at the most detailed level possible). To create the CLC projections, we used CLC level two (primarily due to limitations of the software used for modelling using all the data for mainland Portugal). Level two was also used to compare the results obtained from the LUC datasets with different properties.

The LUCC forecasts were obtained by projecting the geoinformation (fig. 1). The LUC projection period (t_j) never exceeded twice t_i due to the increased uncertainty for more extended periods. The LUCC projection was determined using the IDRISI 17.0 Markov-Markovian transition estimator and Land Change Modeler (LCM) tools. To realize the modelling using that software, it was necessary to convert all the geoinformation to rasters (pixel 25x25m).

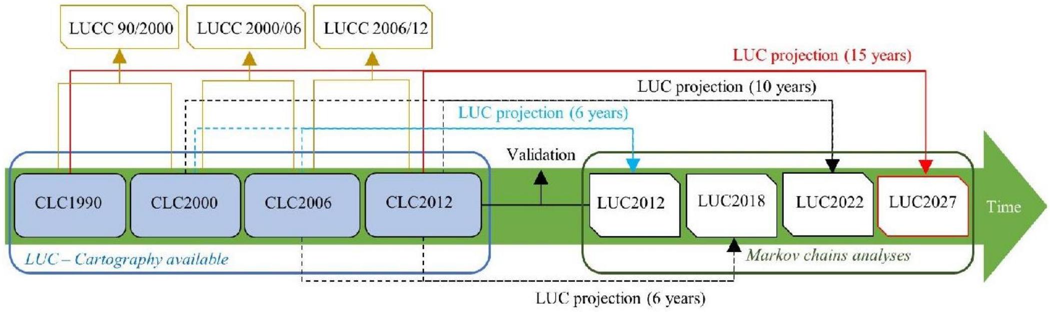

Fig. 1 – Conceptual model of LUCC and LUC projection. Colour figure available online.

Fig. 1 – Modelo concetual das alterações de uso e ocupação do solo e projeção futura. Figura a cores disponível online.

The CA-Markov tool integrates two techniques (Sayemuzzaman & Jha, 2014): Markov chains and cellular automata. A Markov chain is a sequence of random variables $x_1, x_2, x_3, \ldots$ that possesses the Markov property, and random process X(t) is the Markov process for any moment in time such that $t_1<t_2<\ldots<t_n<t_{n+1}$ (Markov, 1971). According to Markov (1971) and Memarian *et al.* (2012), if X[k] is a Markov chain with states $\{x_1, x_2, x_3, \cdots\}$, the probability of a transition from state i to state j in one time instant is (eq. 1).

$$P_{i,j} = \Pr(X[k+1] = j \mid X[k] = i) \quad (1)$$

When a Markov chain has a finite number of states, i.e., n, the transition probability matrix can be obtained (eq. 2), but if the transition probabilities vary with time, the matrix needs to be explicitly written as a function of k (Memarian *et al.*, 2012).

$$\begin{bmatrix} P_{1,1} & P_{1,2} & \cdots & P_{1,n} \\ P_{2,1} & P_{2,2} & \cdots & P_{2,n} \\ \cdots & \cdots & \cdots & \cdots \\ P_{n,1} & P_{n,2} & \cdots & P_{n,n} \end{bmatrix} \quad (2)$$

Cellular automata underline the dynamics of changing events based on the concept of proximity such that regions closer to existing areas of the same class will more probably change to a different class (Memarian *et al.*, 2012).

For the LUCC modelling using CA-Markov, we considered constraint variables, in particular the road layer and the elevation model, assuming that they influence LUCC (Mas, Kolb, Paegelow, Olmedo, & Houet, 2014).

The results of the projection of LUC from 2000-2006 to 2012 (six years) were integrated into the validation process, i.e., the results were cross-compared with the CLC 2012 cartography, resulting in a transfer matrix that allowed us to calculate total accuracy and Kappa coefficients (Congalton & Green, 2009; Jiang, Cheng, Li, Zhao, & Huang, 2014).

At the end of this paper, we will present a brief discussion of the LUC geoinformation properties, comparing the areas of major LUC classes of CLC and those of the official LUC Maps of Portugal (COS) provided by DGT. The COS map legends are compatible with those of the CLC for the first three levels (IGP, 2010).

III. LUC OF PORTUGAL

1. Past LUC in Portugal: spatiotemporal LUCC analysis

The five NUTS II units into which the territory was divided had very different areal distributions of LUC classes in the CLC mapping (fig. 2).

Over the period from 1990 to 2012, the artificial land increased in all NUTS II units, with emphasis on the North, which experienced the greatest increase (in absolute terms) (fig. 2). During that period, new urban areas emerged throughout the territory, especially along the coast and on the outskirts of existing major urban areas (Lisbon and Oporto). The most important of the LUCC was the increase in discontinuous urban fabric, which assumed a greater importance in the north of Portugal.

Overall, soils dedicated to agriculture have decreased, with the exception of NUTS II North, where there was a small increase (fig. 3). The decrease was due primarily to the abandonment of agricultural fields in recent decades, as soils were covered by natural vegetation, including shrublands (DGT, 2013a, 2013b).

When analysing in detail the areas for each subclass of agricultural land (fig. 4), the area of annual crops associated with permanent crops stood out in Alentejo, but there was also a pronounced reduction of that type of LUC (agricultural land) (in absolute terms) in the region between 1990 and 2012. However, the reduction in area occupied with this LUC type was widespread throughout mainland Portugal, but to a lesser percentage when compared with Alentejo, where an increase in olive groves was observed between 2006 and 2012.

In contrast, the land occupied mainly by agriculture, with significant areas of natural vegetation, has increased in recent years (especially in the North), with the exception of Alentejo, where agroforestry systems have predominated (LUC reduction between 1990 and 2012). The complex cultivation patterns in the Centre and North were notable due to the occupied area, but the absolute variation in this LUC was small from 1990 to 2012.

The large forest areas of mainland Portugal are located in the Centre and North (fig. 3). The areas covered in coniferous forests were most important in the Centre (fig. 4), and LUC suffered major transitions during the total period under analysis, on the one hand, due to forest fires that occurred there in past years (Meneses, 2013a) and also due to the planting of other forest species (e.g., eucalyptus trees). In the period under review, high losses were observed in the forest area in those NUTS units, including Lisbon. Alentejo and Algarve showed slight increases in forest area, but in the case of the latter, there was also a reduction in forest area between 2006 and 2012.

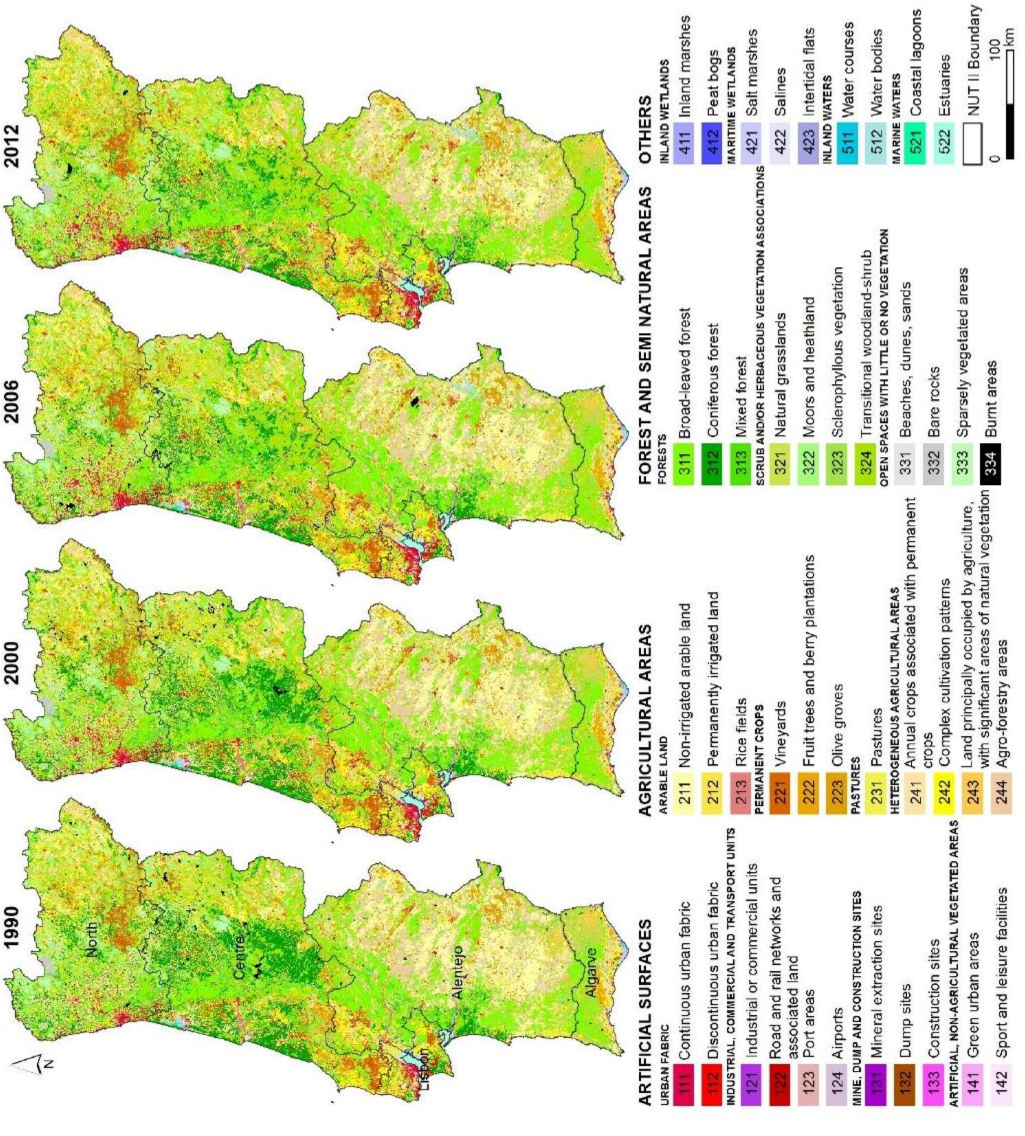

Fig. 2 – Simplified land use and land cover in Portugal in different years (CLC data). Colour figure available online.

Fig. 2 – Representação simplificada do uso e ocupação do solo de Portugal em diferentes anos (dados CLC). Figura a cores disponível online.

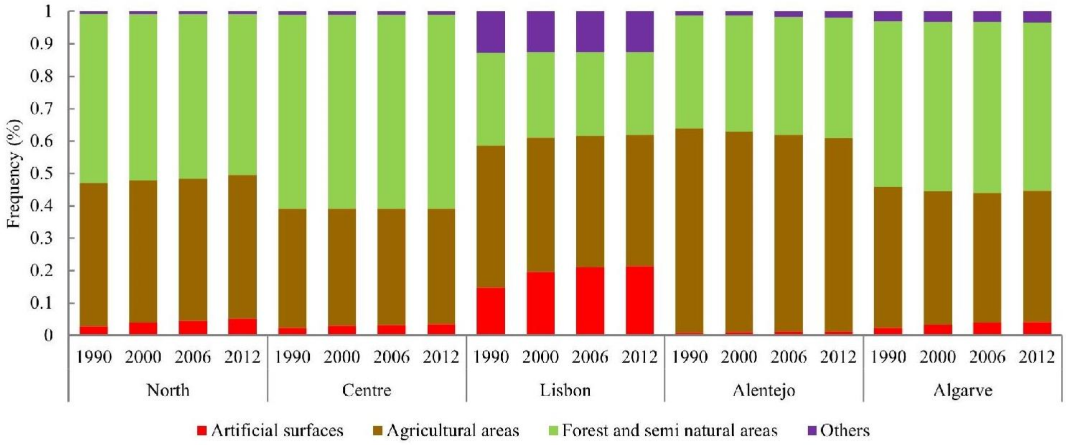

Fig. 3 – Frequency (%) of the main LUC in the NUTS II units of Portugal. Colour figure available online.

Fig. 3 – Frequência (%) das principais classes de uso e ocupação do solo em cada NUTS II (Portugal). Figura a cores disponível online.

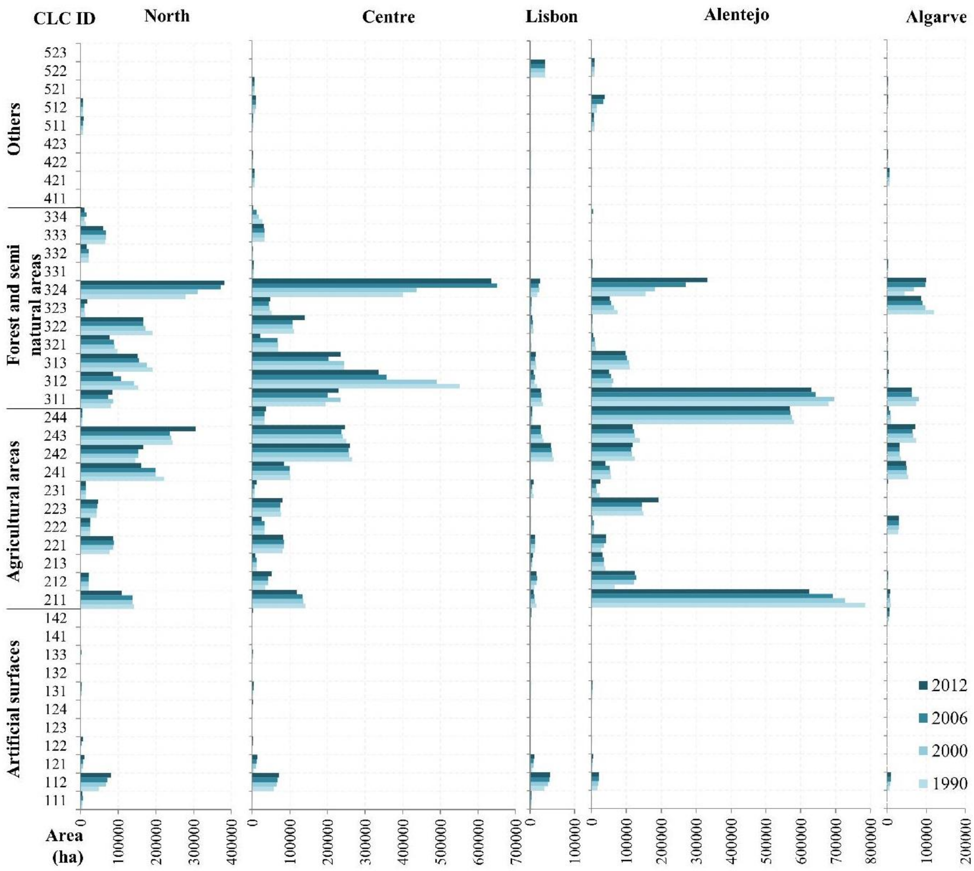

Fig. 4 – LUC area by NUTS II unit in Portugal in different years. See description CLC ID in figure 2. Colour figure available online.

Fig. 4 – Uso e ocupação do solo por NUTS II (Portugal) em diferentes anos. Ver descrição do ID CLC na figura 2. Figura a cores disponível online.

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The other LUC types presented in figure 2 increased except in the Lisbon region, where a slight decrease was observed (fig. 3). This LUC includes water body class (ID 512), and the largest increase in this type of land cover was observed in the Alentejo region due to the construction of the Alqueva dam during the period under analysis, during which a wide area was flooded by the reservoir.

2. Relative LUCC in NUTS II

The detailed analysis of the relative LUCC per NUTS II unit (obtained using the CLC data) showed different spatial and temporal dynamics (table I).

For example, the road and rail networks and spaces associated with them experienced relative increases in the North and in Lisbon between 1990-2000 – reflecting, in part, the investments made in new road infrastructures (Estradas de Portugal, 2015) – whereas the largest increases in this LUC type in the 2000-2006 period were observed in the Centre, Alentejo and Algarve.

The area of industrial or commercial units increased in every NUTS unit in the first period, but the increases were more pronounced in the North, specifically during the last period. These regions showed reversals of the general trend of decreasing area occupied by this LUC type observed in the other NUTS units.

The artificial surfaces showed an increase of 20.15% in discontinuous urban fabric during the first period, with a strong reduction in that growth in the following periods. In contrast, the green urban areas increased in the Centre during the most recent period (11.6%).

Changes between certain agricultural LUC types were also observed in this research, namely, between non-irrigated arable land and irrigated land. The decade of the 1990s registered an increase in permanently irrigated land, especially in Alentejo, where the construction of the Alqueva dam resulted in greater water availability (quantity) and allowed the installation of irrigation systems. This case highlights the influence of anthropogenic interventions on the territory and their contributions to high LUCC over a relatively short period.

In the forested lands, the relative changes in the classes included in this LUC type were small in most cases (<1%), with the exception of burned (ID 334) and sparsely vegetated areas (ID 333) in Alentejo. The class of burned areas for the 2000-2006 period increased by approximately 20% in the same NUTS unit, but in the remaining periods it decreased. Moreover, an increase in sparsely vegetated areas was seen, reflecting, in part, the natural regeneration of vegetation at sites affected by forest fires or by the abandonment of agricultural land. However, it is important to remember that the reduced values in relative LUCC presented in table I represent many hectares due to the areas comprised by each NUTS unit. To illustrate this, the Centre region is a good example, where there was a high absolute reduction in coniferous forests (fig. 4) that did not appear in the relative analysis.

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Table I – Relative LUCC (%) in mainland Portugal by NUTS II unit for the periods 1990-2000 (A), 2000-2006 (B) and 2006-2012 (C). See description CLC ID in figure 2.

Quadro I – Variações relativas de uso e ocupação do solo (%) em Portugal Continental, por NUTS II, nos períodos 1990-2000 (A), 2000-2006 (B) e 2006-2012 (C). Ver descrição do ID CLC na figura 2.

		North			Centre			Lisbon			Alentejo			Algarve		
	CLC ID	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Artificial surfaces	111	0.23	0.03	-0.02	0.01	0.01	-0.01	0.19	0.00	-0.01	0.00	0.01	-0.03	0.06	0.00	0,34
	112	0.38	0.06	0.12	0.14	0.04	0.06	0.28	0.08	0.01	0.15	0.08	0.00	0.34	0.15	0,01
	121	0.82	0.12	0.28	1.19	0.16	0.14	0.45	0.11	0.04	0.68	0.13	0.18	0.98	0.15	-0,05
	122	**20.15**	**5.28**	0.63	1.29	2.95	0.27	3.92	0.33	0.01	0.76	2.80	-0.11	0.00	0.07	0,00
	123	0.42	0.00	0.00	0.21	0.17	0.09	0.05	0.01	0.06	0.00	0.10	0.14	0.31	0.22	0,00
	124	0.37	0.09	0.08	0.15	0.00	0.08	0.04	-0.01	0.01	0.00	0.07	0.22	-0.05	0.00	0,00
	131	1.05	0.20	0.14	1.34	0.16	0.02	0.88	0.06	-0.06	0.83	0.04	0.10	0.61	0.10	-0,02
	132	0.00	1.08	0.01	1.54	0.63	0.43	0.00	0.04	0.36	0.00	0.20	2.35	0.00	0.04	0,06
	133	-0.29	3.31	-0.31	2.03	-0.19	-0.56	1.01	-0.35	-0.12	2.40	-0.58	0.58	0.38	0.02	-0,63
	141	0.81	-0.18	1.90	0.00	0.00	**11.60**	0.05	0.02	0.28	0.00	0.00	0.00	0.00	0.00	0,00
	142	0.53	0.04	0.52	1.39	0.57	0.87	0.95	0.22	0.09	1.41	0.92	0.28	0.56	0.21	0,15
Agricultural areas	211	-0.02	0.00	-0.21	-0.04	-0.01	-0.12	-0.27	-0.05	-0.11	-0.07	-0.05	-0.10	-0.15	-0.09	0,05
	212	-0.01	-0.01	0.05	0.20	0.01	0.23	0.48	0.01	-0.07	0.81	0.05	-0.03	0.19	0.00	-0,08
	213	0.00	0.00	0.00	0.01	0.00	-0.25	0.42	0.03	0.34	-0.06	-0.04	-0.07	-1.00	0.00	0,00
	221	0.15	0.02	-0.04	0.05	0.01	-0.04	0.04	0.00	-0.05	0.36	0.11	0.02	1.04	-0.09	-0,45
	222	0.08	0.00	-0.01	0.02	0.01	-0.26	-0.07	-0.03	-0.06	0.19	0.02	-0.59	0.04	0.00	0,01
	223	0.00	0.00	0.05	-0.04	-0.01	0.08	-0.26	-0.25	0.67	-0.04	0.00	0.33	0.66	0.00	0,90
	231	0.00	0.00	-0.07	0.00	0.09	0.84	-0.36	-0.04	0.73	-0.40	-0.05	0.81	0.28	0.09	0,64
	241	-0.10	0.00	-0.19	-0.01	0.00	-0.15	0.00	0.00	0.02	-0.03	-0.01	-0.26	-0.05	-0.01	-0,05
	242	0.05	0.00	0.08	-0.04	0.00	0.01	-0.06	-0.01	-0.04	-0.06	-0.01	0.03	-0.08	-0.02	0,00
	243	-0.01	-0.01	0.28	-0.04	-0.01	0.04	-0.13	-0.06	-0.02	-0.10	-0.02	-0.04	-0.10	-0.04	0,13
	244	-0.01	0.00	0.05	-0.03	-0.01	0.13	-0.05	-0.08	0.03	-0.01	-0.01	0.00	-0.03	-0.06	-0,54
Florest and semi natural areas	311	0.09	-0.16	0.15	0.21	-0.15	0.15	-0.10	0.00	-0.05	0.02	-0.08	-0.02	0.08	-0.21	0,00
	312	-0.08	-0.25	-0.19	-0.11	-0.27	-0.06	-0.37	0.02	-0.17	0.04	-0.09	-0.10	-0.12	-0.17	0,30
	313	-0.07	-0.12	-0.02	0.00	-0.17	0.16	-0.10	-0.01	0.05	-0.01	-0.06	-0.03	0.16	-0.17	-0,24
	321	-0.07	-0.02	-0.14	0.00	-0.02	-0.68	0.08	-0.11	-0.90	-0.10	-0.11	-0.48	-0.24	-0.11	-0,81
	322	-0.10	-0.03	0.00	-0.03	0.00	0.29	-0.13	-0.03	-0.09	-0.24	-0.08	-0.14	0.00	0.00	0,00
	323	-0.17	0.03	0.60	-0.12	-0.01	0.07	-0.02	0.00	0.02	-0.12	-0.15	-0.05	-0.19	-0.09	-0,03
	324	0.12	0.20	0.03	0.09	0.49	-0.02	0.20	-0.05	0.17	0.17	0.48	0.23	0.53	0.43	0,01
	331	-0.06	0.00	-0.01	-0.05	0.00	-0.09	0.00	0.00	0.00	0.11	0.00	-0.07	0.00	0.00	0,00
	332	0.01	0.00	-0.24	-0.02	0.00	-0.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0,00
	333	0.01	0.00	-0.10	0.02	0.00	-0.08	0.00	0.00	0.00	-0.02	0.00	4.25	0.00	0.00	0,00
	334	-0.28	0.55	-0.29	-0.30	-0.39	-0.73	-1.00	0.00	3.13	-0.93	**20.49**	-0.98	-0.74	-1.00	0,00
Others	411	0.00	0.00	0.00	0.10	0.00	-0.12	0.00	0.00	1.65	0.01	0.05	-0.01	0.00	0.00	0,00
	421	0.02	0.00	0.10	-0.02	0.00	-0.03	-0.05	0.00	0.13	0.02	0.00	-0.01	0.00	0.00	0,00
	422	0.00	0.00	0.00	0.02	0.00	-0.03	-0.01	0.00	-0.17	0.00	0.00	-0.05	0.05	0.00	-0,02
	423	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	-0.19	0.00	0.00	0.00	0.00	0.00	0,03
	511	0.00	0.00	0.04	0.02	0.00	0.19	0.00	0.00	0.00	-0.03	-0.09	0.04	0.00	0.00	0,00
	512	0.19	0.00	0.02	0.23	0.03	0.01	0.19	0.00	0.63	0.11	1.10	0.12	2.63	0.01	0,32
	521	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	-0.08	0.00	0.13	0.00	0.00	0,00
	522	-0.02	0.00	-0.01	-0.06	0.00	-0.04	0.00	-0.01	0.00	0.00	0.00	0.00	-0.03	0.04	0,00
	523	4.05	-0.43	0.00	1.33	0.00	0.00	-1.00	0.00	0.00	-0.16	-0.71	-1.00	-0.59	0.39	0,00
Max.		20,15	5.28	1.90	2.03	2.95	11.60	3.92	0.41	3.13	2.40	20.49	4.25	2.63	0.43	0.90
Min.		-0,29	-0.43	-0.31	-0.30	-0.39	-0.79	-1.00	-0.35	-0.90	-0.93	-0.71	-1.00	-1.00	-1.00	-0.81
Aver.		0,672	0.234	0.078	0.255	0.097	0.278	0.126	0.006	0.151	0.134	0.583	0.134	0.132	-0.003	0.001
S.D.		3,15	0.97	0.35	0.56	0.48	1.82	0.71	0.12	0.59	0.51	3.19	0.81	0.54	0.20	0.28

3. LUC comparison between CLC and COS data

When evaluating LUCC, it is also important to analyse geoinformation properties because different properties may yield different results (Nunes, 2007). For example, the integrated analysis of LUC obtained using COS aggregated data, when compared with that using CLC aggregated data (fig. 5), showed that there were large discrepancies between the total area in some LUC classes, particularly in forested and heterogeneous agricultural areas.

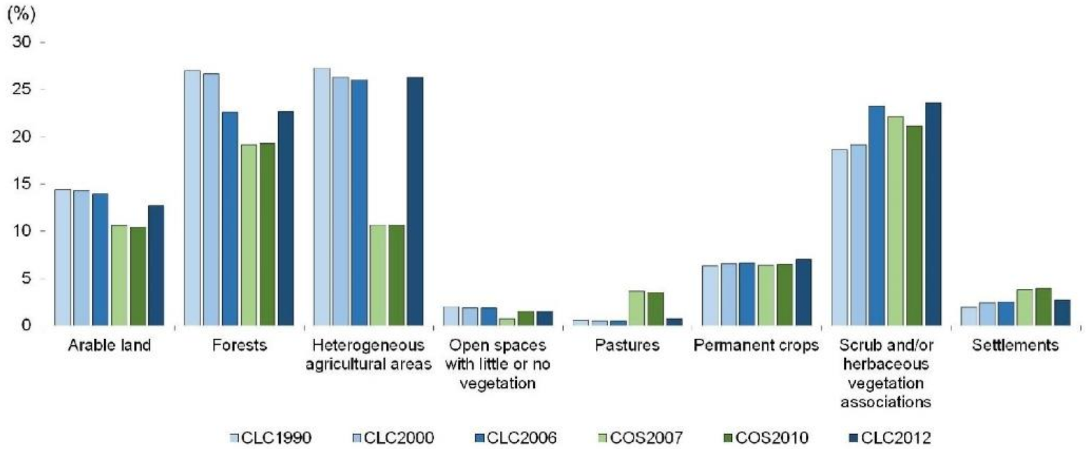

Fig. 5 – Percentages of the areas of the main LUC classes in Portugal obtained from the CLC and COS datasets. Colour figure available online.

Fig. 5 – Percentagem de área das principais classes de uso e ocupação do solo em Portugal, segundo os dados CLC e COS. Figura a cores disponível online.

Overall, the resulting total areas in the temporal sequence presented in figure 5 for each LUC class in the CLC and COS datasets were not in agreement. In the analysis of the expected areas for each type of LUC (fig. 6), it was observed that the class "heterogeneous agricultural areas" from COS 2007 presented greater variations in relation to the observed area, i.e., a 7.3% increase in area was expected.

In this case, the discrepancy between the area observed in each LUC class can be explained by differences in the geoinformation properties, i.e., the COS was more detailed (1:25 000) in comparison with CLC (1:100 000), and the minimum mapping units also differed (1ha versus 25ha, respectively).

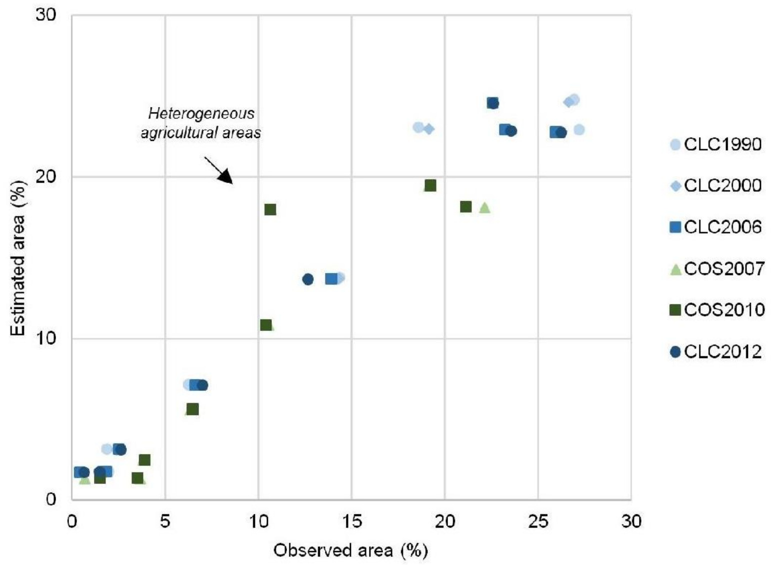

Fig. 6 – Observed versus estimated areas of the main LUC classes in Portugal (CLC and COS datasets). Colour figure available online.

Fig. 6 – Área observada e estimada das principais classes de uso e ocupação do solo em Portugal, segundo os dados CLC e COS. Figura a cores disponível online.

IV. LUCC IN PORTUGAL: MAIN DYNAMICS AND FUTURE LUCC

1. Main LUCC

The LUC in Portugal were highly variable between the years corresponding to the available geoinformation (fig. 7), both in the transitions between the various classes and in the transition areas for each period. Some LUC classes were of greater importance with respect to the transition areas between the various periods, including the transition from "Scrub and/or herbaceous vegetation associations" to "Forests" and the loss of "Arable land" to "Permanent crops" and "Heterogeneous agricultural areas" in the period 2006-2012.

The 1990-2000 and 2000-2006 periods showed less significant variations between the different LUC classes (level II) in relation to the other periods, with only LUC dynamics (gains and losses) in the Forest and Scrub classes and/or herbaceous vegetation associations (changes >1% of total area, i.e., >89,258.2ha).

Analysing in detail each NUTS unit (fig. 7), the North and the Centre NUTS units presented primary LUCC very similar to those observed in the total area (mainland Portugal). However, the Lisbon and Algarve NUTS units stood out, with greater variations in the main LUCC (>0.5% area of each NUTS unit) in comparison with other classes, especially the transitions to urban fabric and heterogeneous agricultural areas. In Alentejo, large LUCC were observed during the two initial periods (between forests and scrub and/or herbaceous vegetation associations), but between 2006 and 2012, the arable land transitions stand out among the other classes, including the transitions to permanent crops (48,293.6ha), heterogeneous agricultural areas (17,864.4ha) and scrub and/or herbaceous vegetation associations (22,087.8ha).

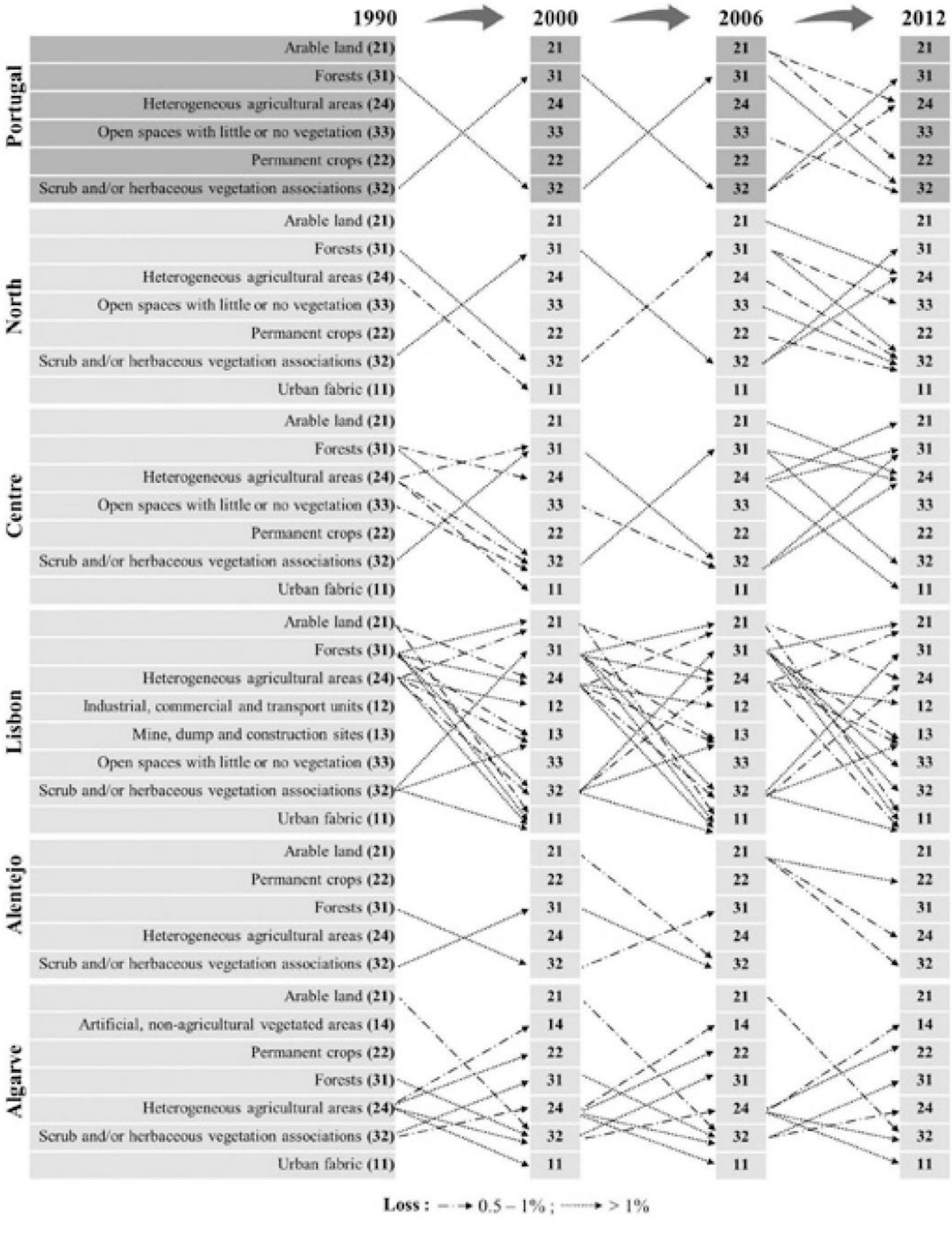

Fig. 7 – Main LUC dynamics in mainland Portugal (% area of the total territory) and NUTS units (% area of each NUTS unit).

Fig. 7 – Principais dinâmicas do uso e ocupação do solo de Portugal Continental (% de área do territorio total) e NUTS (% de área de cada NUTS).

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The heterogeneous agricultural areas are those that had higher LUCC in the NUTS units, both as transitions from other types of LUC (gains) and in losses of area for other LUC types.

However, this LUC class does not excel when used to analyse the LUCC in Portugal, revealing the importance of undertaking LUCC evaluations at different scales.

2. LUCC in Portugal: future trends

In the results obtained using CA-Markov, it was observed that the LUCC were predicted to be highly variable until 2027 in Portugal, with some LUC classes expected to greatly increase, and others were expected to greatly diminish in absolute terms (fig. 8).

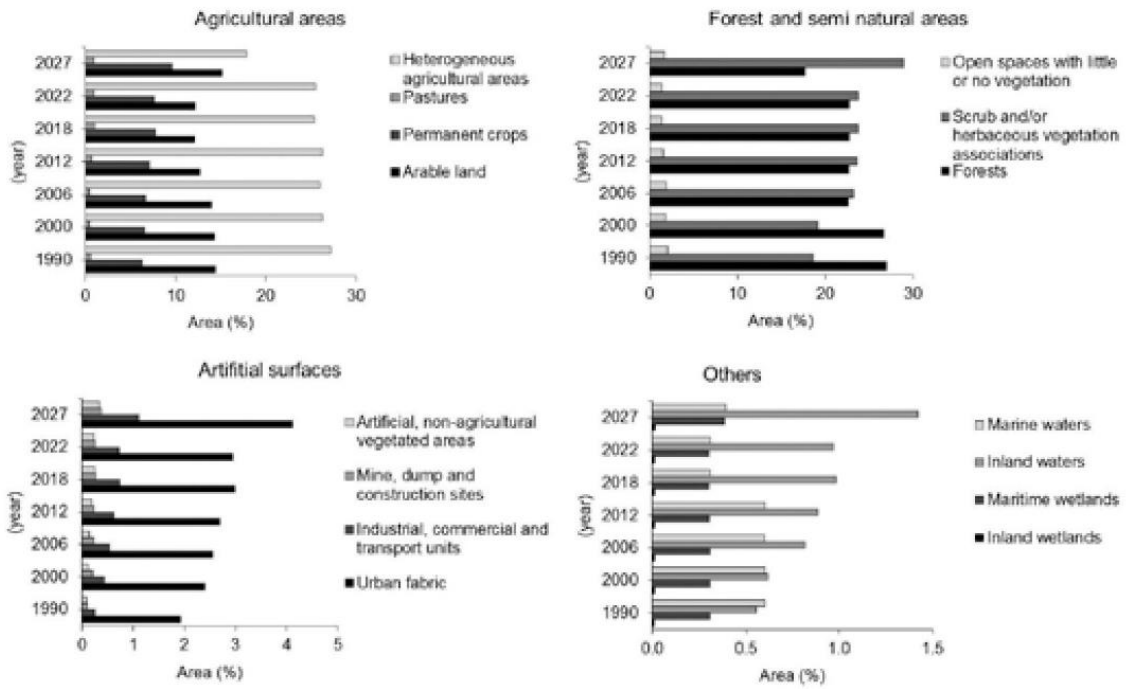

Fig. 8 – LUC areas in mainland Portugal in the past (CLC data, level II) and the LUC projections to 2018, 2022 and 2027.

Fig. 8 – Uso e ocupação do solo em Portugal Continental no passado (dados CLC) e a projeção para 2018, 2022 e 2027.

In the group of agricultural classes, the most significant trend involved the heterogeneous agricultural areas that had the largest land covers but that presented a high likelihood to reduce until 2027. The arable land varied over the several years of the projection but maintained a balance at the end of the total projection period. The LUC classes with smaller areas tended to increase slightly.

The most important facts regarding the subclasses within the forest and semi natural areas were the increase in the scrub and/or herbaceous vegetation associations and the reduction in the forests (mainly coniferous forests). Reduced variations were seen in the open spaces with little or no vegetation.

The "others" LUC group was not very expressive when considering area. However, there was a high probability for an increase in artificial surfaces, with the most relevant fact being the increase up to double in areas of urban fabric and industrial, commercial and transport units. This LUC group showed an increase in inland waters.

3. Validation of the LUC projections

Based on the intersection between CLC 2012 and LUC2012 as a result of the projections of the CLC data for 2000 and 2006, we obtained a high level of concordance between the two maps. The overall accuracy and Kappa coefficient were high: 90.3% and 87.9%, respectively.

However, there were inconsistencies between CLC 2012 and LUC projected to 2012 (approximately 10% of the total area). The largest observed discrepancies were mostly in the forests and scrub and/or herbaceous vegetation associations.

The projected forest areas presented approximately 2% less area and an increase of 4% when compared with the areas of those classes in CLC 2012. The class of scrub and/or herbaceous vegetation associations presented the opposite situation (a reduction of 4% and an increase of 2%). From the transition matrix obtained from CLC 2012 and projected LUC to 2012, it was observed that a large part of the inconsistency in the areas belonged to the sub-classes of these two main LUC types (forests and scrub and/or herbaceous vegetation).

V. DISCUSSION

In this research, large LUCC were observed in the Portuguese territory, and those changes were also very different at the regional level, highlighting the existing territorial idiosyncrasies.

At a worldwide level, forests have suffered large LUCC in past decades, especially the gross reductions between 2000 and 2005 (13.5 million ha per year) (FAO & JRC, 2012), and Portugal has contributed to those large losses in forests. The successive reduction of forest area in mainland Portugal is the most important fact to retain from the results of the absolute LUCC analysis, with emphasis on the coniferous forest in the Centre region. Also notable are the large LUCC between sub-classes that make up the main forest class.

Forests in Portugal have been decimated by the high recurrence of forest fires (Meneses, 2013b) and by the extent of events that have caused the loss of large forest patches (Gomes, 2006; Oliveira, Pereira, & Carreiras, 2012). Forest regeneration in this territory is complex because most of the burned areas were composed of resinous trees. Given the very short recurrence times of these events, the regeneration of this type of vegetation becomes more difficult and depends on factors such as fire severity (Maia, Pausas, Vasques, & Keizer, 2012), post-fire environmental conditions (Calvo *et al.*, 2008). Most parts of the burned areas have primarily given way to scrub and/or herbaceous vegetation associations.

The reductions of conifer forest also contributed nematodes of *Pinus pinaster*, which have affected large extensions of the forests (Autoridade Florestal Nacional, 2012).

However, as we highlighted from the LUC projection results, there was a predicted trend of high reductions in forest area until 2027 (approximately -10% of the total area of Portugal). These results are a consequence of the tendency of LUCC that have occurred in recent years, namely, the reduction in forested areas in the Portuguese territory. However, these results do not consider the driving forces that led to past LUCC, which could vary if there was a way to integrate them in these projections. It should also be noted that the uncertainties associated with LUCC increase when increase the projection period.

The discrepancies observed between the projected CLC2012 and the LUC2012 can reflect natural or anthropic phenomena that have occurred in the territory, for example the interference of forest fires, as those events were not considered in the CA-Markov modelling but have been responsible for large LUCC in this territory.

The model presents some limitations with regards to LUC projection, i.e., the trends that were derived from the input data (LUC) were considered, but integrated socioeconomic, environment or other types of data that impact LUCC were not considered. The LUCC are spatio-temporally very dynamic, and depending on the projection period, there could be other driving forces to consider (e.g., economic assistance, the founding of communities, and new technologies) (Meneses *et al.*, 2017) or catastrophic events (e.g., forest fires) (Regos, Ninyerola, Moré, & Pons, 2015). The projected LUCC obtained using only LUC could not be predicted with absolute accuracy. If the model integrated this extra information, the projected LUC might change. Some limitations of this type of modelling were also referred to in Memarian *et al.* (2012), in particular the complex variability within the land cover categories, limitations resulting from using only two land cover maps for calibration, and the limitations caused by CA that affect spatial but not temporal distributions.

The urban fabric and the industrial, commercial and transport units featured increased probabilities, continuing the growth in the trends recorded in past years and following the tendency of increased artificial areas reported by EEA (2017). However, urban sprawl is very dependent on other variables such as socio-economic factors (Carballada & Marques, 2016), the supply and demand of goods and services, and territorial management instruments (Salvati, Sateriano, & Bajocco, 2013; Meneses, Vale, *et al.*, 2014). In this research, we also observed incongruities in the results of the relative LUCC of the regions, namely, in continuous urban fabric between 2006 and 2012, which presented negative values (table I). This result (though the numbers involved were small) may reflect the different guidelines used in the creation of CLC 2012 and its associated validation, the influence of human factors when creating specific cartographic works in the same way (different photointerpretation teams), or errors in photointerpretation, because other studies using different LUC datasets have presented increasing tendencies in past decades

(Meneses, Vale, Reis, & Saraiva, 2013; Meneses, Saraiva, *et al.*, 2014; Vale *et al.*, 2014; Caetano, Igreja, Marcelino, & Costa, 2017).

Large LUCC was observed in agricultural land, especially in the Alentejo region, where the construction of the Alqueva dam resulted in the planting of new agricultural crops (extensively) and the development of other activities such as rural tourism and agritourism (Roca & Leitão, 2005; Daniel, 2010; Meneses *et al.*, 2017, 2013). This region has seen the largest increase in olive groves, essentially due to irrigation, which was only possible due to the large capacity of water released from the dam referred to earlier (DRAPA, 2013). The other regions also exhibited LUCC in agricultural areas, many of which were planted with different types of crops, but there were also transitions for other LUC types (e.g., forests or urban areas). In the North, the difficulties small farms have faced when adapting to agricultural markets, low education or training, the ageing population and the lack of financial resources have led to a lack of investment and ultimately to the abandonment of this activity (Amorim, 1993).

The economic crisis of recent years in Portugal also contributed to the observed LUCC, namely, to declines in urban growth and the demand for rural agricultural areas derived from the migration of the "new rural" that are part of the process of urban exodus (Ribeiro, 2013), i.e., the return of some urban populations to cultivate agricultural fields which were previously abandoned or occupied by LUC types other than agriculture. However, many of these abandoned agricultural areas are also the result of emigration in rural areas that has occurred in recent years (Jacinto & Ramos, 2010; Ribeiro, 2013). Shortages of work, poorly paid work, a lack of opportunities and other socio-economic factors have led to rural emigration and should therefore be considered as factors that have contributed to the increase in the abandonment of agricultural areas (Dayton-Johnson, Pfeiffer, Schuettler, & Schwinn, 2009).

In past spatial LUCC analyses and projections, there were limitations because the models were not fully prepared to integrate data from the driving forces that are at the base of certain LUCC (Pang, Li, Wang, & Hu, 2010; Yu *et al.*, 2011; Kanianska, Kizeková, Nováček, & Zeman, 2014; Aroengbinang, 2015). On the other hand, LUCC are not linear in time or space (Pang *et al.*, 2010). For example, forest losses can result from several factors such as a succession of catastrophic events (e.g., forest fires in hot and dry years), increasing demand for forest materials (wood or other), or simply by conversion to artificial land resulting from an urban growth process (e.g., buildings and road networks).

The complexity of the integration of driving forces (e.g., economic, social, and political) in the determination of future LUCC has also been referred to in the Portuguese context (Ribeiro, Vale, & Reis, 2014). For example, the simple construction of the large Alqueva dam (inaugurated in 2004) culminated in large LUCC in the Alentejo region in the last decade, particularly transitions from non-irrigated to irrigated agricultural land (Meneses *et al.*, 2017). In this case, it would not be possible to predict and spatially determine the LUCC derived from the construction of the dam using only the LUC inputs from 1990 and 2000 (CLC) until 2006 (the year of the CLC cartography).

The comparisons of the total areas of the main CLC and COS classes revealed some discrepancies in area in the time series presented in figure 5. Although these two types of LUC cartography were prepared with different purposes, they are frequently used in evaluations of LUCC, but it must be realized that different results and, consequently, different interpretations of LUCC can be obtained depending on the properties of the geoinformation integrated into models for evaluating LUCC. Therefore, when comparing LUCC described in several studies (e.g., Pôças *et al.*, 2011; DGT, 2014; Teixeira *et al.*, 2014; Meneses, Reis, Vale, & Saraiva, 2015), it must be quite clear what kind of LUC geoinformation was used in the analyses.

VI. CONCLUSIONS

In Portugal, large LUCC have occurred in recent years, especially in forested and agricultural lands. In general, the spatio-temporal LUCC have been very diverse in this territory. Some LUC classes featured high reductions in area in one period but in subsequent periods revealed that the reductions slowed, or vice versa. On the other hand, it was observed that the LUCC were not spatially proportional. For example, whereas the Lisbon region presented strong artificial land increases, in other regions the same LUC type increased slowly (e.g., Alentejo). In the case of the forests in the Centre, there were high losses, whereas Alentejo presented a slight increase in forest area; in Algarve, there was an increase in the initial period and a reduction in the final period.

In relative terms, the LUCC were also quite variable temporally and spatially, but this analysis has provided evidence of more specific LUCC, both in area losses and in increases in area of LUC types relative to the initial situations. For example, for the relative increases observed in areas occupied by road and rail networks and associated land, industrial or commercial units and in burned areas observed in certain NUTS units, the LUCC obtained was irrelevant when employing an absolute analysis. However, relative analyses of LUCC are important to understand in detail certain LUCC resulting from certain driving forces, such as the high investments in the road network in recent years.

LUC dynamics are very specific to the times used when deriving conclusions for some study areas. The 1990-2000 period was characterized by large transitions of "scrub and/or herbaceous vegetation associations" to other classes of LUC (e.g., forest), which illustrates this statement, but a similar situation was observed during 2006-2012 for other LUC classes. The case of forest land is also notable for those periods, primarily because forest lands increased due to the transition from "scrub and/or herbaceous vegetation associations", but at the same time there was a loss of forest areas to "open spaces with little or no vegetation". In the second period, however, the major losses and gains were essentially the results of transitions between "forests" and "scrub and/or herbaceous vegetation associations".

The projections of the LUC results showed a high tendency for the reduction of heterogeneous agricultural areas and forests and increases in open spaces with little or no vegetation. However, modelling using CA-Markov presented limitations in the projections of LUCC because the driving forces data (e.g. socioeconomic and environmental data, policies, and others) at the base of the determined LUCC were not considered.

LUC area discrepancies were observed between the main classes of CLC and COS, highlighting the different properties of each LUC dataset. In this sense, the properties of geoinformation that integrate the models to LUCC assessments are also important because LUC datasets with different properties can lead to different results, which in turn lead to different interpretations and conclusions regarding the LUCC in the same territory.

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Understanding Driving Forces and Implications Associated with the Land Use and Land Cover Changes in Portugal

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Abstract: Understanding the processes of land use and land cover changes (LUCC) and the associated driving forces is important for achieving sustainable development. This paper presents the LUCC in Portugal at the regional level (NUTS II) from 1995 to 2010 and discusses the main driving forces and implications associated with these LUCC. The main objectives of this work are: (a) to quantify the land use and land cover (LUC) types (level I of LUC cartography) by NUT II in Portugal for the years 1995, 2007 and 2010; (b) to assess the spatio-temporal LUCC; and (c) to identify and discuss the main driving forces of LUCC and corresponding implications based on correlations and Principal Components Analysis. The results revealed large regional and temporal LUCC and further highlighted the different and sometimes opposite time trends between neighboring regions. By associating driving forces to LUCC, different influences at the regional level were observed, namely LUCC into agriculture land derived from the construction of dams (Alentejo region), or the conversion of coniferous forest into eucalypt forest (Centre region) associated with increased gross value added (GVA) and employment in industry and forestry. Temporal differentiation was also observed, particularly in the settlements that expanded between 1995 and 2007 due to the construction of large infrastructures (e.g., highways, industrial complexes, or buildings), which is reflected on employment in industry and construction and respective GVA. However, certain LUCC have implications, particularly in energy consumption, for which different behavior between regions can be highlighted in this analysis, but also on land-use sustainability.

Keywords: LUC; LUCC; land management; driving forces; implications; LUC sustainability

1. Introduction

The land use and land cover (LUC) of territories is changing and these transitions have influences in the landscape [1–4]. The evaluation of these changes, both spatially and temporally, is increasingly important in the context of the sustainable use of the territories [5]. The evaluations of land use intensity and also the land use and land cover changes (LUCC) with environmental, economic and social impacts are particularly important in this context [6–8].

Methods for the preparation of land cover mapping have evolved, in particular, the methods of data retrieval by remote sensing (supervised or unsupervised analyses) that fostered the proliferation of studies about LUCC in different territories and scales [1,9–14].

Landscape changes have been evaluated around the world by different authors (e.g., [15–22]), using different models and tools (e.g., artificial neural network, Conversion of Land Use and its

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Effects at Small regional extent—CLUE-S, Dinamica EGO, Cellular Automata (CA) MARKOV, Land Change Modeler-IDRISI, Cellular automata, Multi-Agent Systems, Spatial autocorrelation, GWR, etc.) and different geographic datasets (thematic maps, satellite images, institutional LUC cartography at different scales, among others).

Deforestation is currently a major problem due to its large effect on the reduction of air and water quality and climate changes [23,24]. These LUCC have indirect influence on the environment and contribute to the reduction of the quality of life, and further affect all living beings that depend on specific life conditions in the territories subject to these LUCC. In some countries, forest land has been turned into agriculture land [25–28]. In order to maximize the agricultural production, some soils are being intensively exploited through the use of machinery and agrochemicals [29–32]. However, the intense use of these soils generates negative impacts that contribute to the physiochemical and biological degradation of them [33], some of which are currently undergoing desertification process.

Another current issue is the high artificialization of soils [12], mainly explained by the urban expansion process [34–39] that include the construction of roads, telecommunications infrastructures or urban facilities [4]. Soil sealing reduces the infiltration of rain water into the soil [40,41] and consequently the runoff increases, often causing floods, loss of human lives and material damage.

There are several research studies involving LUCC assessments that aim to identify the driving forces (e.g., [3,22,42]) and studies about the impacts on the environment, economy and society, and its influence on the development of the territories [11,43–45].

The driving forces of land changes have been categorized into different types, such as economic, cultural, social, political, and, in some cases, may include two or more categories simultaneously [13,46–48]. However, the changing patterns can be the result of a complex interaction between different driving forces at different scales of action and LUC [49]. The proven relationships between the LUC and economic variables have been analyzed and explained in detail [50,51]. It is also important to consider the temporal component of the driving forces in this analysis [46] in order to understand if these have the same influence on LUCC over time, but also to figure out if these temporal variations are similar (among regions).

Landscape changes that occurred in the last decades in Portugal have been evaluated in some parts of the territory and in different contexts, such as the LUCC estimation in the LANDYN Project [52], in the reporting of emissions and carbon sequestration in the LUC sector and in governmental reports [4], and other publications revealing clear evidence of LUCC [52–56]. These studies show that the great landscape transitions that occurred in the last decades in Portugal, derived largely from LUCC along the coastal areas with the increase of land artificialization and reduction of forest land due to forest fires and anthropic actions [28].

The evaluation of LUCC is crucial for landscape changes assessments and evaluation of territorial dynamics, as well as for the implementation of new investments, policy development (sustainability development) [37] and spatial planning actions among others. However, the assessment of landscape changes that quantifies the full spatial variations to allow regional differentiation, as well as the temporal variations to identify the main driving forces, has not yet been made in Portugal.

The identification of driving forces associated with LUCC has been done in different locations and in different contexts in Portugal, e.g., LANDYN Project, detecting the relationship between LUCC and the resulting impacts on natural resources, such as water [3,57]. On the other hand, these studies do not address the identification of the relationships between LUCC and socio-economic disturbances in land-use planning. This topic has already been studied by other researchers albeit in other study areas [19,35,58,59].

In this context, the current research has the following objectives: (a) to quantify the LUC types (level I of LUC cartography) by NUT II in Portugal for the years 1995, 2007 and 2010; (b) to assess the spatio-temporal changes (LUCC); and (c) to identify and discuss the main driving forces of LUCC and corresponding implications (socio economic and environment factors).

2. Study Area

The study area is Portugal (only Continental Portugal, 88,962.50 km^2), a European country divided into five NUTS II (Nomenclature of Territorial Units for Statistics, level II): North, Centre, Lisbon, Alentejo and Algarve.

The relief in Portugal is quite irregular, characterized by deep incised valleys surrounded by mountains in the North and by lower less rugged relief in the South. The climate is strongly influenced by the Atlantic Ocean and the Mediterranean Sea, performing the transition between the Mediterranean and the Atlantic climatic conditions. The rainfall regime is characterized by high spatial and inter-seasonal variability. The mean annual precipitation (MAP) ranges from less than 500 mm, in the south and northeast, to more than 2000 mm, in the northwest. The spatial variation of MAP reflects the influence of latitude, elevation and distance to the ocean. In fact, MAP tends to increase with increasing latitude, elevation and proximity to the Atlantic. Summer months (June, July and August) are particularly dry and the rainfall concentrates, mainly, in the period lasting from October to March.

The population is concentrated along the coast, especially in the metropolitan areas of Lisbon and Oporto. In recent years, some cities in the countryside have expanded towards the periphery (e.g., Viseu in Centre region), but rural areas still prevail. Some urban macrocephaly can be found in the study area which resulted from the concentration of activities and population that once migrated towards the large urban centers and settled there (rural exodus) [60].

In Portugal, there are large spatial contrasts in terms of LUC (Figure 1), within the NUTS II coinciding with large spatial variations of LUC for the years 1995, 2007 and 2010 (Table 1).

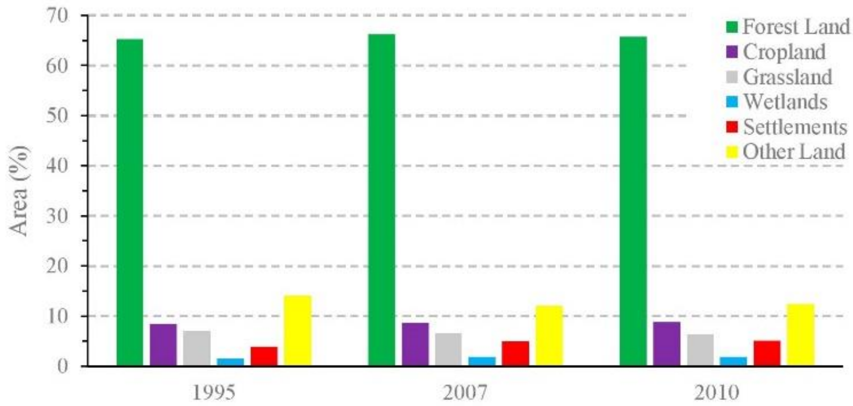

Figure 1. Land use/cover area of Portugal in 1995, 2007 and 2010.

Forest land and others LUC occupy more than 65% of the LUC of the country showing different spatial distributions. The Northern region is dominated by pinewoods (*Pinus pinaster*), rain-fed crops and shrub land, whereas, in the Centre region, these types of occupation are also dominant but there is a higher percentage of land occupation with *Eucalyptus*, which differentiates the forest species in comparison to the Northern region. The LUC of the Lisbon Region is dominated by rain-fed crops and settlements. In Alentejo, the forest is totally differentiated from the previous regions with predominance of evergreen oaks (*Quercus suber* and *Quercus rotundifolia*), rain-fed crops, and even with high percentage of grassland. Shrub land is predominant in Algarve and this region is also characterized by the dominance of *Quercus suber* in forest areas (Figure 2).

Table 1. Area (%) of Portugal by LUC types in NUTS II for the years 1995, 2007 and 2010.

LUC		North (23.93% of Total Area)			Centre (31.70% of Total Area)			Lisbon (3.32% of Total Area)			Alentejo (35.44% of Total Area)			Algarve (5.62% of Total Area)		
Level I	**Level II**	**1995**	**2007**	**2010**	**1995**	**2007**	**2010**	**1995**	**2007**	**2010**	**1995**	**2007**	**2010**	**1995**	**2007**	**2010**
Forest Land and others	*Pinus pinaster*	3.86	3.98	3.95	8.93	8.46	8.35	0.29	0.28	0.28	0.99	0.96	0.95	0.07	0.07	0.07
	Quercus suber	0.39	0.40	0.39	0.63	0.70	0.70	0.26	0.26	0.26	7.72	8.06	8.11	0.82	0.85	0.85
	Eucalyptus	1.49	1.70	1.87	3.52	4.67	4.80	0.16	0.15	0.15	2.21	2.26	2.25	0.35	0.36	0.36
	Quercus rotundifolia	0.09	0.10	0.09	0.54	0.55	0.55	0.00	0.00	0.00	5.96	5.73	5.72	0.31	0.30	0.30
	Other quercus	1.24	1.31	1.31	0.97	1.04	1.05	0.00	0.00	0.00	0.07	0.07	0.07	0.00	0.00	0.00
	Other broadleaves	1.23	1.99	1.43	0.88	1.08	1.09	0.07	0.08	0.08	0.30	0.30	0.31	0.18	0.17	0.17
	Pinus pinea	0.00	0.01	0.01	0.07	0.11	0.11	0.15	0.17	0.17	1.11	1.55	1.56	0.26	0.49	0.49
	Other coniferous	0.05	0.07	0.07	0.05	0.09	0.09	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	Rain-fed crops	3.45	2.90	2.88	4.33	3.62	3.62	0.50	0.44	0.43	6.17	5.42	5.28	0.40	0.36	0.36
	Irrigated crops	1.61	1.36	1.37	1.47	1.49	1.50	0.36	0.32	0.31	1.21	1.43	1.42	0.05	0.05	0.05
	Rice	0.00	0.00	0.00	0.12	0.12	0.12	0.02	0.04	0.05	0.26	0.25	0.26	0.00	0.00	0.00
Cropland	Vineyards	1.08	1.23	1.24	0.68	0.66	0.65	0.13	0.12	0.12	0.38	0.46	0.47	0.03	0.02	0.02
	Olive	0.96	1.03	1.05	1.55	1.36	1.36	0.03	0.03	0.03	2.23	2.29	2.48	0.33	0.31	0.31
	Other permanent	0.25	0.32	0.32	0.34	0.34	0.33	0.04	0.03	0.03	0.05	0.06	0.06	0.37	0.34	0.34
Grassland	Grassland	0.40	0.38	0.36	1.43	1.51	1.45	0.27	0.26	0.26	4.59	4.21	4.10	0.29	0.23	0.23
Wetlands	Wetlands	0.21	0.21	0.21	0.37	0.39	0.40	0.20	0.20	0.20	0.50	0.76	0.77	0.20	0.21	0.21
Settlements	Settlements	1.34	1.67	1.72	1.29	1.64	1.70	0.55	0.69	0.71	0.42	0.58	0.60	0.19	0.28	0.30
Other Land	Shrubland	5.54	4.89	5.28	4.19	3.53	3.52	0.26	0.23	0.22	1.20	0.96	0.95	1.72	1.52	1.51
	Other Land	0.72	0.39	0.38	0.31	0.32	0.32	0.02	0.02	0.02	0.07	0.08	0.08	0.04	0.05	0.05

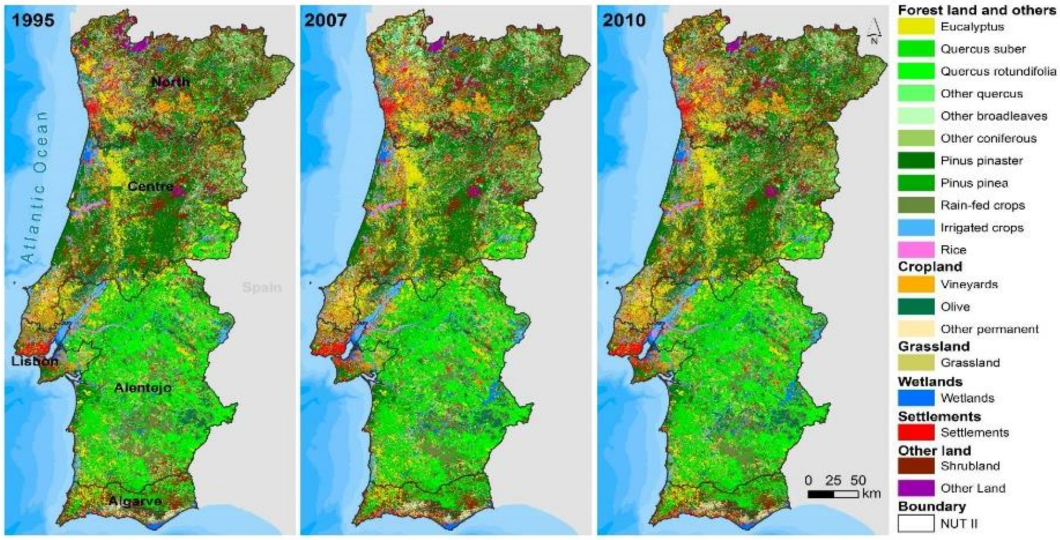

Figure 2. Spatial distribution of LUC in Portugal in 1995, 2007 and 2010. Data source: DGT.

3. Data and Methods

Figure 3 presents the methodological scheme used in the LUC cartography, LUC type variations, spatio-temporal LUCC, driving forces and implications assessments.

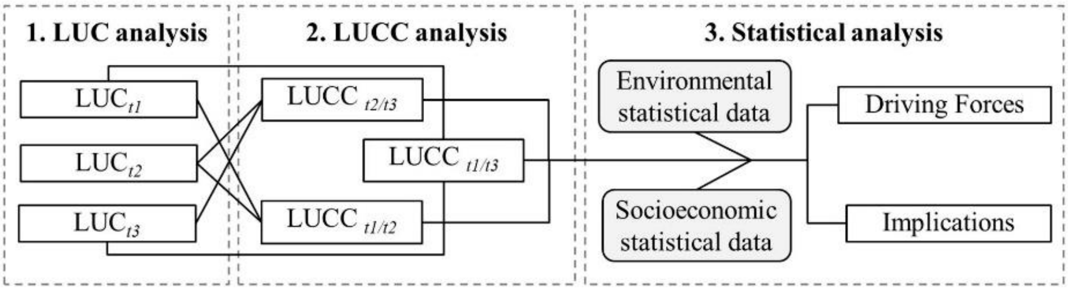

Figure 3. Methodological scheme used in the LUCC and driving forces and implications assessment.

3.1. LUC Cartography

The LUC data used in the evaluation of the LUCC of Portugal are derived from Land Cover Maps of Portugal for the years 1995, 2007 and 2010 produced by the General Directorate for Territorial Development (DGT), using a nomenclature (hierarchical) defined to support Kyoto reporting of emissions and carbon sequestration in Portugal [4]. The LUC data have the following characteristics: scale 1/25,000; 1 ha of minimum mapping unit; vectorial data model (polygons); and minimum distance of 20 m between lines. These are the most recent LUC data with higher cartographic detail for the complete study area. The cartographic information of 2007 was obtained from photointerpretation of orthophotos (0.5 × 0.5 m), a process aided by IRS and AWIFS satellite imagery and geographic information of cadastral surveys (agriculture and forestry) done at DGT. All results were validated (geometrically and thematically) in order to obtain data with high accuracy and quality [61]. The DGT used for the LLUC cartography of 2010 the same methodology used for the cartography of 2007. The LUC cartography of 1995, also produced by DGT, was obtained using the vectorial data of LUC boundaries of 2007 that were updated to the 1995 LUC, based on orthophotos and satellite images of this year.

In the present work, the LUC cartography for the year 1995 is only available with the nomenclature used in the Kyoto report. For this reason, and in order to allow LUC comparison between different periods, the legend of the LUC maps of 2007 and 2010 follows the nomenclature used in the Kyoto report.

LUC maps were created for the years 1995, 2007 and 2010, followed by the assessment of losses and gains of area by LUC type between the different years. LUC types include the level I, corresponding to the principal LUC (forest land and others, cropland, grassland, wetlands, settlements and other land), disaggregated into level II (Table 1).

LUC cartography of Portugal with similar characteristics was available only for those years that have conditioned the choice of LUCC analysis periods: the first period comprises 12 years, and the last three years. This can influence the presented results, especially when comparisons are made between the two periods, regarding LUCC, driving forces and implications. We have opted for the in-depth analysis of the relative variations calculated for each period.

3.2. LUC Type Variations

The variance between main groups of LUC types (corresponding at level I of LUC cartography) that differ from the average is obtained by the following coefficient of variation:

$$L_{cv} = \left(\frac{\sigma}{\overline{A}}\right) \times 100\% \quad (1)$$

where L_{cv} is the coefficient of area variation of the LUC group i in a time series, σ is the standard deviation area of the classes (level II) that integrated the group of LUC (level I) and $\overline{A}$ the mean area of these classes (level II).

The measure of relative dispersion, L_{cv}, is used to evaluate and compare different distributions of LUC areas, i.e., the variability of the areas relative to the mean. Small values of L_{cv} are related to more homogeneous data sets (in this case, areas of the LUC types—level II—that integrated the principal LUC class corresponding to level I). Temporal changes in area by LUC type were obtained using the following equations [44]:

$$A_k = A_{t2} - A_{t1} \quad (2)$$

$$A_{kr} = \frac{A_{t2} - A_{t1}}{A_{t1}} \times 100\% \quad (3)$$

where A_k is the absolute variation area of the determined LUC type for the period k, A_{t1} is the area in the initial period, A_{t2} is the area in the final period and A_{Kr} refers to the relative variation area of determined LUC type for the period k.

The quantification of LUC is an innovation to the DGT data because there is a lack of comparisons at the national level (level I) made with the LUC nomenclature using the Kyoto report [4]. Furthermore, the coefficient of area variation (L_{cv}) is original as there are no comparisons between the LUC groups for the three periods under analysis.

3.3. Spatio-Temporal LUCC

To further understand the dynamics of transition between the various types of LUC, the thematic maps (Figure 2) (vector data) of the different years were crossed. The analysis of LUCC is supported by transfer matrices [62,63]:

$$A_{ij} = \begin{vmatrix} A_{11}\ A_{12}\ \ldots\ A_{1n} \\ A_{21}\ A_{22}\ \ldots\ A_{2n} \\ \ldots\ \ldots\ \ldots\ \ldots \\ A_{n1}\ A_{n2}\ \ldots\ A_{nn} \end{vmatrix} \quad (4)$$

where A_{ij} refers to the changed area from the i LUC type for period k to the j LUC type for the period $k + 1$, and n is the number of LUC types.

Using the transfer matrix the kappa coefficient is also calculated [64] to assess the spatial agreement of all the LUC products of the different years, using the following equation:

$$K = \frac{N \sum_{i=1}^{m} P_{li} - \sum_{i=1}^{m} (P_{pi} \times P_{li})}{N^2 - \sum_{i=1}^{m} (P_{pi} \times P_{li})} \quad (5)$$

where K is the Kappa coefficient, N is the total area, and P_{pi} and P_{li} are the areas in the row and rank, respectively, of a given LUC type.

The results of the variations by LUC type (areas) were correlated among the NUTS II. This procedure is intended to find relationships between the LUCC of different periods obtained from the data previously submitted and to determine if there are regional differences in the LUCC in the study area.

3.4. Driving Forces and Implications

Statistical data (socioeconomic and environmental) collected from the databases available on the web of the National Statistics Institute of Portugal (INE), National System of Hydrological Resources (SNIRH) and Pordata (Table S1 in Supplementary Materials) for the correspondent years of LUC data were used for the analysis of the driving forces and implications associated to LUCC. This analysis is primarily based on the identification of correlations between all collected data (see Supplementary Materials, Table S1) with the previously determined LUCC. Only the variables presented in Table 2 (driving forces and implications) were considered in the study because these are the ones that have the higher correlation with the LUCC (calculated previously) determined for different regions of Portugal.

The information about subsidies and agro-environmental measures was also considered when selecting the variables driving forces and implications. However, these data are not available for the entire period under analysis.

Table 2. Socioeconomic and environmental statistical data considered in analysis.

Variable		Description
Driving forces	CP	Cereals production (kg)
	EI	Export intensity (%)
	EMPA	Employment (No.)—agriculture, forestry and fishing
	EMPI	Employment (No.)—industry, construction and water
	EMPT	Employment (No.)
	ERPBL	Environmental revenues (€)—protection of biodiversity and landscape
	ERWM	Environmental revenues (€)—waste management
	GVAA	Gross value added (€)—agriculture, forestry and fishing
	GVAI	Gross value added (€)—industry, construction and water
	OTP	Olive trees production (kg)
	PCGDP	Per capita gross domestic product (€/per inhabitant)
	PCPP	Per capita purchasing power (%/per inhabitant)
	Rd	Roads (km)
	RP	Resident population (No.)
	VP	Vineyard production (kg)
	VSW	Volumes stored by watershed (10^6 m^3)
Implications	CEEA	Consumption of electric energy (kWh)—agriculture, forestry and fishing
	CEED	Consumption of electric energy (kWh)—domestic
	CEEI	Consumption of electric energy (kWh)—industry, construction and water
	CEET	Consumption of electric energy (kWh)—total
	ECA	Electricity consumers (No.)—agriculture, forestry and fishing
	ECD	Electricity consumers (No.)—domestic
	ECI	Electricity consumers (No.)—industry, construction and water
	ECT	Electricity consumers (No.)—total
	EEPBLPC	Environmental expenditure (€/per inhabitant)—protection of biodiversity and landscape
	EETPC	Environmental expenditure (€/per inhabitant)—total

A multivariate exploratory technique, the Principal Components Analysis (PCA), was performed using the software Statistica 7 (Stat Soft. Inc., Tulsa, USA) to develop the exploratory analysis of socio-economic and environmental standardized data with the LUCC. When performing this analysis for each type of LUC, only the variables that had a high correlation with LUCC were selected. Redundant variables were excluded from this analysis.

In recent decades, there were significant changes in areas occupied by water bodies [28], especially in the Alentejo, due to the construction of the Alqueva dam. Therefore, the volumes stored by watershed (VSW) were also considered, to find relationships with changes in area of irrigated crops or other LUC that need water. The VSW were analyzed separately with the LUCC, because the Lisbon region (NUTS) does not have any reservoirs or water storage. The watersheds were grouped according to their location in each NUTS and the average of all watersheds was considered for two years (year of LUC cartography and the previous one).

4. Results

4.1. Land Use/Cover Types Variations

The LUC suffered wide changes and transitions between 1995 and 2010. According to Figure 4, the settlements distribution show that, on average, the deviations from the mean value of the areas of all the LUC classes reached approximately 14.5% of the settlements. The wetlands distribution reaches 10%, decreasing to 1% in the last distribution (forest land). It should be noted that intermediate changes in the classes that integrated each principal group of LUC (level I) can occur during this analysis, i.e., certain LUC classes (level II) can reduce their area and increase it later or vice versa, which requires a more detailed analysis of LUCC. These results are innovative and important to understand the LUCC in this territory.

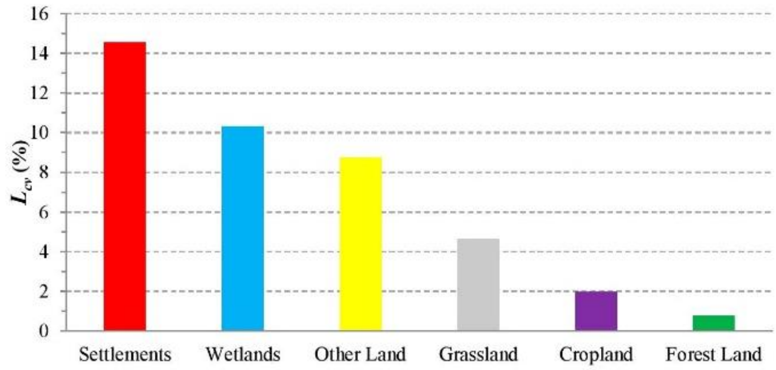

Figure 4. Coefficient of variation (L_{cv}) of LUC (level I) in Continental Portugal (years 1995, 2007 and 2010).

The class of settlements increased during the overall period under analysis owing, largely, to the urban sprawl of metropolitan areas (Lisbon and Oporto). However, the heaviest urbanization of soils occurred along the coastal areas [65], mainly in the North, Lisbon and Algarve. Major investments in road construction throughout the country were made during this period. This generalized artificialization of land is reflected in the results of the settlements coefficients of variation (L_{cv}) shown in Figure 4 (each group corresponding to level I of LUC, see bold legend in LUC maps).

The wetlands class also increased between 1995 and 2010, which is explained by a large increase in the construction of new dams or reservoirs for the use of surface water for energy production and for the supply of the populations and their activities (agricultural and industrial). The infrastructure with the largest contribution to the increase in the area occupied by wetlands was the Alqueva dam (Alentejo) that comprises a reservoir of about 250 km^2. However, in some cases, new infrastructures that were built around these new water bodies resulted in landscape fragmentation. This process of landscape fragmentation in wetlands has been investigated in different locations, because of its implications on the degradation of its ecological functions [64].

The other land class presented a L_{cv} very close to the wetlands (Figure 4). This class includes shrub land and other types of LUC. However, the first type of occupation can evolve into forest or can be lost due to the occurrence of forest fires, which are very frequent in Portugal [24,66,67]. This class ranges approximately 9% in the L_{cv}. The smallest coefficients of variation of LUC were observed in cropland and forest areas. L_{cv} results show that large variations of LUC occurred in the settlements group, in relation to the area occupied by these types of LUC in the year 1995.

The LUC transitions shown in Tables S2–S4 presented in the Supplementary Materials, registered a Kappa coefficient above 81% for the different periods under analysis (Table 3) and a high percentages of overall unchanged LUC areas. In the complete period between 1995 and 2010 overall changes reached 16.6%.

Table 3. Spatial agreement of LUC between different periods (see Supplementary Tables S2–S4).

Periods	Overall Unchanged (%)	Overall Changes (%)	Kappa Coefficient (%)
1995–2007	84	16	82.4
2007–2010	97.1	2.9	96.6
1995–2010	83.4	16.6	81.8

4.2. Spatio-Temporal Transitions

In Portugal, there are large spatial contrasts in terms of LUC (Figure 2). For the years 1995, 2007 and 2010 (Table 1), the largest spatial variations of LUC are visible at the NUTS II level of analysis.

LUCC analysis was differentiated in absolute (ha) and relative (%) terms in order to understand the landscape changes of each Portuguese region (Figure 5) between 1995 and 2010. Regarding the absolute variations (Figure 5A), the most important change is the loss of forest in the Centre of Portugal. The forest land area in relative terms does not present significant variations in the country, although this result does not reflect the internal transitions that occurred in this main LUC type.

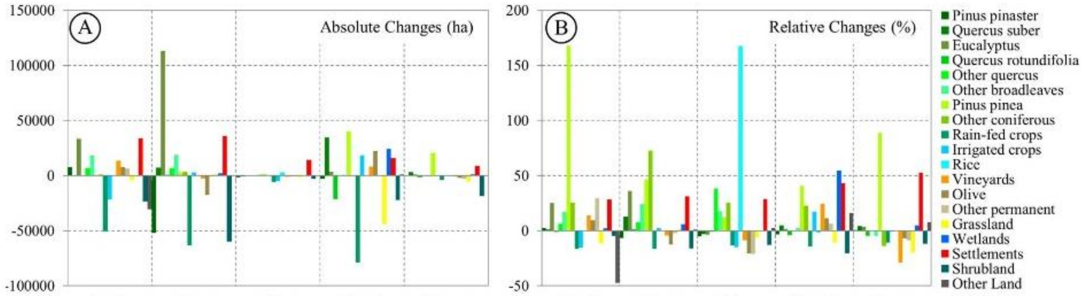

Figure 5. Absolute (**A**); and relative (**B**) LUCC in NUTS II of Portugal (1995–2010).

A sharp reduction of *Pinus pinaster* and shrub land can also be observed in Central. The reduction of *Pinus pinaster* forests and *Pinus pinea* is due to the transition to *Eucalyptus*, shrub land, settlements, other broadleaves and rain-fed crops is the most important (see Table S4 in the Supplementary Materials). This LUC type has been affected by forest fires [24] fueled by the presence of a high number of resinous trees, forest maintenance and lack of shrub land cleaning. Forest fires cause major changes in the landscape, have destroyed a large part of the Portuguese forests [24,68,69] and the recovery of burned areas (pine forest) is very slow when the natural vegetation is regenerated without human intervention. The LUCC in Portugal are not unique within the larger picture of European LUCC, for example the reduction of pine forest in Catalonia (NE Spain) also caused by several forest fires [70].

Figure 5A shows that in the North and Centre regions there has been a large increase in the area occupied by *Eucalyptus*, settlements, and a reduction in the area of rain-fed crops. The significant transition of *Pinus pinaster* into *Eucalyptus* is explained by the investments in this type of forest to meet the demand of raw material for the cellulose industry [71]. *Eucalyptus* is a fast-growing tree that allows several cuts in shorter time-periods, thus ensuring a higher yield for the producer. Furthermore, the high incidence of pinewood nematode vector in the region of Alentejo (coast) and in the Centre region was responsible for heavy losses of pine trees [72].

In relative terms, the variations of the different LUC types by NUTS II between 1995 and 2010 are very different, as shown in Figure 5B. In the North and in the Algarve, there was a high increase in the areas occupied by *Pinus Pinea* (175% and 85%, respectively), while in the Centre there was an increase in the areas taken by other coniferous (70%).

In the Lisbon region, there was mostly an increase in settlements when the absolute changes are observed (Figure 5A). Indeed the increase of settlements has taken place all across the country albeit more pronounced in the Alentejo and Algarve in relative terms (Figure 5B), owing largely to the construction of new resorts and other infrastructures to cater for the increase in tourism in recent decades [73]. This land artificialization was the result of the marked transition that occurred on soils occupied by rain-fed crops, irrigated crops, *Pinus pinaster* and shrub land. However, between 2007 and 2010 the transition from irrigated crops was lower when compared with other types of LUC previously mentioned, indicating an increase in the use of agricultural land that had suffered from abandonment and disinvestment during the last two decades [74]. The increase of the urban areas was also observed in other Mediterranean regions [5].

In relative terms the Lisbon region registered a rise of 170% in the area dedicated to rice crops between 1995 and 2010, and to a lesser degree in the soil occupied by other *quercus*.

In the Alentejo region the absolute changes in LUC show an increase of *Quercus suber* and other coniferous, and wetlands, followed by a high reduction of area occupied by rain-fed crops and grassland (Figure 5A); the dryland was converted into irrigated land due to the greater availability of water resulting from the construction of the Alqueva dam [28,52]. In relative terms, the Alentejo shows an increase of 60% of wetlands areas due to the area occupied by the reservoir of the Alqueva dam, which spurred the intensification of irrigated crops, vineyards and olive trees. These LUCC are thus considered as water-dependents [13] highlighting the availability of water in quality and quantity for the LUC transitions. The expansion of water bodies provided an increase of water storage thus allowing the conversion of certain types of LUC to irrigated areas, and partially justifying the increase in the area of these types of LUC in the total period under review. Some examples of the expansion of agricultural areas in lowland Bolivia [26] and the increasing area dedicated to olive trees in the Mediterranean region [75] can be found in the literature.

Absolute changes of LUC in the Algarve region were characterized by an increase in the area occupied by *Pinus pinea*, settlements and by the reduction of soil occupied by shrub land. The same trend is observed in the relative changes, including the reduction of vineyards and grassland areas (Figure 5B).

When LUCC are analyzed per time variations (Δ1995–2007 and Δ2007–2010) different results of correlation coefficients (r) and coefficients of determination (r^2) were obtained (Table 4). The Northern Region showed an increase in area for several types of LUC during the first period; however, a large proportion of these showed a decline in the second period, which accounts for the negative correlation shown in Table 4. The remaining NUTS II show a positive correlation of LUCC for the two periods, with the higher correlation in the relative changes observed in Lisbon. These results show that the LUCC tendency is very similar in the two periods in Lisbon. Although the majority of the relative changes in the remaining NUTS have positive correlations, they are not very high. It is worth noting that the analysis of the results should consider that the time periods do not have the same length which can condition the results of the LUCC dynamics.

Table 5 presents all possible correlations of the LUCC between each NUTS II. It is possible to observe higher correlations between LUCC of the NUTS II between the two dates (bold values in Table 5). However, we would like to stress the proximity effect of the NUTS II in LUCC with the closest NUTS showing positive correlation. This fact is explained by the distribution of different types of LUC throughout Portugal, where there is a high variation of area with LUC type between regions. The results show that the NUTS North and Algarve have the highest positive correlations in two periods for the relative changes, reflecting mainly the increase of *Pinus pinea* and settlements, and the reduced area occupied by grassland. These last results indicate similar trends in relation to variations of these LUC classes.

Table 4. Correlation (r) and determination (r^2) coefficients between areas of LUCC (absolute and relative changes) obtained to the different periods (dataset 1: 1995–2007; dataset 2: 2007–2010) (significance level $p < 0.05$).

NUTS II	Absolute Changes		Relative Changes	
	r	r^2	r	r^2
North	−0.67	0.45	−0.15	0.02
Centre	0.72	0.52	0.45	0.20
Lisbon	0.80	0.63	0.80	0.65
Alentejo	0.62	0.39	0.22	0.05
Algarve	0.49	0.24	0.35	0.12

Table 5. Correlation coefficients between LUCC area variations (absolute and relative changes) between all NUTS II combinations (significance level $p < 0.05$).

NUTS II		Absolute Changes			Relative Changes		
Input 1	Input 2	1995–2010	1995–2007	2007–2010	1995–2010	1995–2007	2007–2010
North	Centre	**0.68**	**0.58**	0.15	**0.56**	**0.56**	0.16
	Lisbon	**0.63**	**0.52**	−0.07	0.04	0.13	0.00
	Alentejo	**0.51**	0.41	0.02	0.43	0.41	0.07
	Algarve	0.36	0.40	−0.16	**0.74**	**0.71**	0.07
Centre	Lisbon	0.41	0.42	0.16	0.17	0.33	0.04
	Alentejo	0.40	0.44	0.15	0.47	0.42	0.40
	Algarve	0.39	0.39	0.21	0.45	0.44	0.28
Lisbon	Alentejo	0.38	0.39	0.25	0.00	0.02	0.28
	Algarve	0.48	0.47	**0.63**	0.13	0.22	0.11
Alentejo	Algarve	**0.57**	**0.61**	0.22	0.55	**0.56**	0.14

4.3. Driving Forces and Implications of the LUCC

The LUCC vary considerably over time in the NUTS II, but it is necessary to understand the driving forces in the LUCC in each region and possible resulting implications. The obtained correlations between socio-economic and environmental data available for the three years under review (see the variables in Table 2) and the LUCC (Table 6) show that variations of settlements correlate strongly with the employment (according to INE classification includes the following activities: agriculture, forestry, fishing, industry, construction and water), volume of exports, gross value added (industry, construction and water activities); resident population and roads. The previous factors are the driving forces behind the increase on artificial surfaces.

The changes in resident population per NUTS are positively correlated with the increase in settlements, owing largely to the construction of infrastructures (housing, commercial and industrial) during the last decade of the 20th century [28]. The LUCC for settlements has some implications, in particular, the increase in energy consumption by domestic and industrial consumers that showed high positive correlations (bold values in Table 6).

Table 6. Correlation coefficients average values between the LUCC areas of the NUTS and the driving forces and implications variables for the complete period (significance level $p < 0.05$).

		Land Use/Cover Classes																	
		Pinus pinaster	*Quercus suber*	*Eucalyptus*	*Quercus rotundifolia*	Other *quercus*	Other broadleaves	*Pinus pinea*	Other Coniferous	Rain-Fed crops	Irrigated crops	Rice	vineyards	Olive	Other permanent	Grassland	Wetlands	Settlements	Shrubland	Other Land
Driving forces	CP	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.94**	0.67	**0.93**	n.a.	n.a.	n.a.	**0.96**	**0.87**	n.a.	n.a.	n.a.
	EI	0.55	−0.04	0.49	−0.02	**0.77**	**0.76**	−0.22	**0.70**	0.48	**0.81**	0.11	**0.86**	0.35	−0.07	n.a.	n.a.	n.a.	n.a.	n.a.
	EMPA	**0.97**	−0.31	**0.80**	−0.27	**0.91**	**0.81**	−0.47	**0.93**	0.42	**0.75**	−0.01	**0.75**	0.31	0.56	n.a.	n.a.	**0.89**	n.a.	n.a.
	EMPI	0.51	−0.49	0.21	−0.48	**0.85**	**0.83**	−0.65	**0.71**	0.08	0.52	−0.41	**0.84**	−0.09	0.24	n.a.	−0.38	**0.83**	n.a.	n.a.
	EMPT	0.42	−0.59	0.11	−0.57	0.66	0.60	**−0.71**	0.62	−0.12	0.32	−0.42	0.60	−0.29	0.01	n.a.	−0.46	**0.75**	n.a.	n.a.
	ERPBL	**0.73**	−0.28	0.65	−0.24	0.62	0.62	−0.37	**0.77**	0.20	0.47	0.03	0.47	0.14	0.31	−0.08	0.01	**0.74**	0.44	0.39
	ERWM	0.38	−0.31	0.31	−0.31	0.58	0.63	−0.37	0.64	−0.01	0.30	−0.21	0.55	−0.04	0.24	−0.25	−0.16	**0.72**	0.43	0.29
	GVAA	**0.73**	0.40	**0.85**	0.45	0.55	0.48	0.21	0.53	**0.90**	**0.89**	0.63	0.57	**0.84**	0.16	0.61	n.a.	n.a.	0.52	0.53
	GVAI	0.44	−0.48	0.21	−0.46	**0.71**	**0.71**	−0.61	0.69	−0.02	0.40	−0.34	0.70	−0.16	0.07	−0.39	n.a.	**0.83**	0.55	0.56
	OTP	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.80**	**0.74**	n.a.	n.a.	**0.84**	n.a.	n.a.	**0.73**	n.a.	n.a.	n.a.
	PCGDP	−0.42	−0.13	−0.40	−0.16	−0.45	−0.41	0.05	−0.31	−0.52	−0.51	−0.15	−0.46	−0.44	−0.36	−0.24	−0.13	−0.25	−0.56	−0.54
	PCPP	−0.52	−0.36	−0.65	−0.38	−0.51	−0.52	−0.23	−0.41	**−0.72**	−0.66	−0.40	−0.54	**−0.73**	−0.48	−0.47	−0.43	−0.37	n.a.	n.a.
	Rd	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.74**	n.a.	n.a.
	RP	0.43	−0.54	0.13	−0.52	**0.71**	0.67	−0.68	0.64	−0.05	0.39	−0.40	0.69	−0.22	0.03	−0.45	−0.43	**0.78**	0.58	0.64
	VSW	0.25	0.58	0.55	0.57	0.01	−0.02	0.55	0.10	0.68	0.63	**0.72**	0.17	**0.79**	−0.56	0.65	**0.87**	0.18	−0.17	−0.02
	VP	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.89**	n.a.	n.a.	n.a.	0.33	**0.80**	n.a.	n.a.
Implications	CEEA	0.44	0.51	**0.75**	0.52	0.20	0.20	0.46	0.38	0.65	0.64	**0.71**	0.26	**0.71**	−0.14	0.64	**0.79**	n.a.	n.a.	n.a.
	CEED	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.77**	n.a.	n.a.
	CEEI	**0.73**	−0.41	0.55	−0.38	**0.80**	**0.74**	−0.57	**0.87**	0.19	0.60	−0.12	**0.71**	0.04	0.15	−0.22	−0.15	**0.93**	n.a.	n.a.
	CEET	0.47	−0.49	0.25	−0.48	0.65	0.62	−0.61	0.69	−0.06	0.36	−0.29	0.59	−0.19	0.03	−0.38	−0.32	**0.80**	n.a.	n.a.
	ECA	**0.97**	−0.24	**0.87**	−0.20	**0.90**	**0.81**	−0.40	**0.96**	0.46	**0.78**	0.07	**0.74**	0.36	0.53	0.00	n.a.	n.a.	n.a.	n.a.
	ECD	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	**0.80**	n.a.	n.a.
	ECI	0.64	−0.44	0.35	−0.42	**0.90**	**0.85**	−0.61	**0.76**	0.21	0.61	−0.32	**0.85**	0.04	0.35	−0.31	−0.29	**0.83**	n.a.	n.a.
	ECT	0.49	−0.58	0.20	−0.56	**0.70**	0.66	**−0.71**	**0.70**	−0.09	0.35	−0.39	0.63	−0.25	0.08	−0.47	−0.42	**0.82**	0.53	0.56
	EEPBLPC	−0.32	−0.26	−0.35	−0.29	−0.42	−0.41	−0.06	−0.24	−0.61	−0.59	−0.25	−0.52	−0.52	−0.14	−0.35	−0.23	−0.25	−0.50	−0.52
	EETPC	−0.66	−0.09	−0.62	−0.13	**−0.75**	−0.70	0.16	−0.65	−0.69	**−0.86**	−0.26	**−0.80**	−0.53	−0.08	−0.27	−0.20	**−0.71**	−0.68	**−0.76**

CP—Cereals production (kg); EI—Export intensity (%); EMPA—Employment (No.), agriculture, forestry and fishing; EMPI—Employment (No.), industry, construction and water; EMPT—Employment (No.); ERPBL—Environmental revenues (€), protection of biodiversity and landscape; ERWM—Environmental revenues (€), waste management; GVAA—Gross value added (€), agriculture, forestry and fishing; GVAI—Gross value added (€), industry, construction and water; OTP—Olive trees production (kg); PCGDP—Per capita gross domestic product (€/per inhabitant); PCPP—Per capita purchasing power (%/per inhabitant); Rd—Roads (km); RP—Resident population (No.); VP—Vineyard production (kg); VSW—Volumes stored by watershed (10^6 m^3); CEEA—Consumption of electric energy (kWh), agriculture, forestry and fishing; CEED—Consumption of electric energy (kWh), domestic; CEEI—Consumption of electric energy (kWh), industry, construction and water; CEET—Consumption of electric energy (kWh), total; ECA—Electricity consumers (No.), agriculture, forestry and fishing; ECD—Electricity consumers (No.), domestic; ECI—Electricity consumers (No.), industry, construction and water; ECT—Electricity consumers (No.), total; EEPBLPC—Environmental expenditure (€/per inhabitant), protection of biodiversity and landscape; EETPC—Environmental expenditure (€/per inhabitant), total; n.a.—not applicable.

The forest land changes have different correlations with the variables considered in different subtypes of LUC covered by this class (Table 6). Employment in agriculture, forestry and fishing is the most important driving force in forest land changes, especially changes in areas occupied by *Pinus pinaster*, *Eucalyptus*, others *quercus*, broadleaves, coniferous and irrigated crops. In the case of *Eucalyptus*, the area variation was high, especially in the Centre (location of major pulp mills); this increase was reflected on the conversion of forested areas into *Eucalyptus* forest which brought about an increase in electricity consumption associated with the industrial sector, which is an implication derived from this type of LUCC.

LUCC of rain-fed and rice crops presented a high positive correlation with cereals production. The first type of LUC shows high correlation with the gross value added in the agriculture sector. In the case of variations of irrigated crops, there was a high positive correlation with the gross value added in agriculture sector, volume of exports, employment in agriculture and olive trees production. Although the LUC cartography of the irrigated crops is different from that of the olive groves, the statistical data include all the irrigated productions including the irrigated olive production from Alentejo. In recent years, the increase in number of irrigated plantations and new olive groves was due to the construction of a new dam and other infrastructures for water storage. These findings are attested in the case of irrigated olive groves in an extensive cultivation, especially in the Alentejo region, contributing to the increase of the gross value added in the agriculture, forestry and fishing.

It is noteworthy that, regarding the cropland class, the changes in the areas of vineyards correlated positively with wine production, volume of exports and employment in agriculture and industry. However, these LUCC also indicate the increase in electric energy consumption and in the number of electricity consumers in agriculture and industry.

The variation of the volumes stored by watershed is also clear in LUCC, especially in cultures that require water, as well as in the areas of expansion of the main water bodies in the total period under review. As for the variations of environmental expenditure in protection of biodiversity and landscape, this exhibit negative correlation with the LUCC which are potentially explained by fragmentation of LUC, indicating higher LUCC area mean lesser environmental expenditure or vice versa.

The per capita gross domestic product and the per capita purchasing power variables have very weak correlations with the LUCC. The per capita purchasing power presents a high negative correlation with the rain-fed and olive crops. These results can be explained by the increase and efficiency of the cereals and olive productions (increase of production volume in smaller areas) but also by the supply and demand of the food products markets and their derivatives from the types of LUC.

As previously explained, the LUCC in Portugal are associated with different driving forces, resulting in different implications at the regional level. These results were obtained using the Principal Component Analysis (PCA) performed with the LUCC in five NUTS II and the respective variables of driving forces and implications of these LUCC (Figure 6). These results showed distinct groupings among regions and also some asymmetry between driving forces and implications (Figure 6A,B). For example, the driving forces with LUCC of the Alentejo and Algarve regions in factor 1 (Figure 6A) present the higher positive values, while in the case of the implications (Figure 6B) the results are the opposite. According to the obtained results, factor 1 can be related with the spatial distribution of the regions and factor 2 identifies, in general terms, the LUCC associated with the driving forces as well as the implications.

Loadings of factor 1 of the driving forces analysis (Figure 6A) highlight the PCGDP and PCPP variables (0.47 and 0.59, respectively). The temporal analysis of these variables showed an increasing trend over time and also an effect of spatial continuity between the NUTS (increasing values from the North region to Lisbon and decreasing to the Algarve). These observations, in particular the effect of spatial continuity between NUTS, are also evident for the loadings of factor 1 of the implications analysis (Figure 6B), highlighting the high positive loadings for the CEEI and ECI variables (0.9 and 0.91, respectively).

The analysis of the loadings for the factor 2 of the driving forces analysis (Figure 6A) reflected the positive influence of the GVAA and OTP variables (0.60 and 0.68, respectively) representing the main driving forces for the analyzed LUCC. In the case of factor 2, the implications analysis (Figure 6B) highlights the CEEA positively (0.73). This variable constitutes one of the main implications of the observed LUCC. Among the considered LUCC and driving forces (Figure 6A), there is a clear distinction between the northern (North, Centre and Lisbon) and southern (Alentejo and Algarve) regions of Portugal. In fact, the landscape changes can be the result of the influence of regionally distinct factors (job offer, agricultural productivity, and water availability), culminating in the fragmentation of the territory. This fragmentation is also referred to in EEA reports [76] and Ribeiro et al. [77].

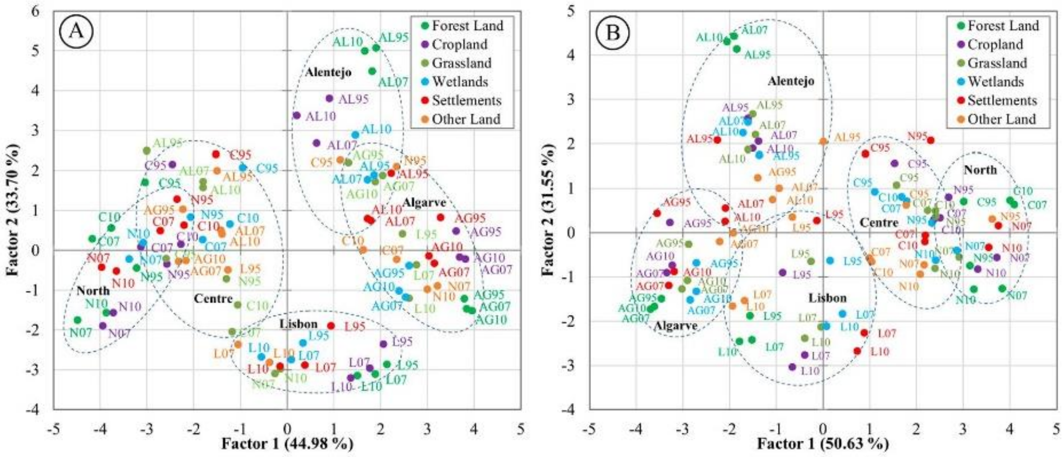

Figure 6. Principal components results of the LUCC classification and driving forces (**A**) and implications (**B**) variables by NUTS II for the complete period. N, North; C, Centre; L, Lisbon; AL, Alentejo; and AG, Algarve; and the numbers after the letter correspond to the year: 95, 1995; 07, 2007; and 10, 2010.

When performing the analysis of LUCC and its implications (Figure 6B), the clusters formed by regions are not so well defined (greater proximity or linkage distance) as in the case of driving forces, but there is still an approximation between them, providing a continuity from north to south or vice versa (Figure 6A,B). This means that implications associated with LUCC are observed in a spatially threaded process, with less demarcated transitions between regions when compared with the driving forces. These implications associated with environmental repercussions of LUCC have been mentioned by Chen et al. [78], and can include interference in energy sustainability in order to produce more energy (need for more dams, wind and photovoltaic farms and supply networks) to assure the energy demands of consumers (industry, agriculture and population). However, more energy supply also creates new possibilities to generate new LUCC.

5. Discussion and Conclusions

In Portugal, the LUCC are not static in time and space, because LUC that characterizes these landscapes is very dynamic along the total period under analysis. This LUCC dynamics are also referred to in other studies carried out in other territories (e.g., [17,20,63,79]).

In this research, LUCC exhibits different regional trends that are conditioned by the latitude factor, which was proved by the higher correlation among regions with higher spatial neighborhood. Different regional trends are also explained by different types of dominant LUC that characterize these regions at a certain time. The results show that the LUCC are differentiated for each NUTS II, considering the relative variation of area for each LUC type.

LUCC results are generally in line with other studies carried out in other areas, such as the increase of the urban areas (e.g., [55,80–82]) and the reduction of forest areas (e.g., [83–85]).

Crosschecking the area of LUCC with socio-economic and environmental indicators allowed the identification of the factors that have the greatest influence on LUCC, and consequently on landscape changes and ecological pressures (forest land degradation). However, the LUCC have different variations in the considered periods, in particular, the measures, policies and investments applied in each region. Thus, it was found that the landscape of Portugal suffered some changes between the analyzed periods, but this spatial differences are derived from certain LUCC in different regions, especially the resinous forest transition to other types of land cover (e.g., North and Centre) as well as the artificialization of soils (important in the Algarve region). The latter is marked essentially by the urban growth, that characterizes the complex urban system of the Iberian Peninsula [86,87]. These new land cover types exert great pressures on the territory's ecosystems and they can cause problems in their sustainability, in particular in the consequent degradation of more fertile soils and other natural resources (e.g., drinking water) [36,57].

The temporal analysis of the driving forces results (Figure 6A) shows that the regions maintain proximity in most types of the LUC analyzed. However, there are some exceptions such as the settlements with greater linkage distance between 1995 observations and those of 2007 and 2010. Portugal went into economic recession in the last decade and this factor may have contributed to a slowdown in construction, which was particularly marked in the Centre and North regions where a higher percentage of settlements is located. According to Auch et al. [46] during times of recession new development typically declines and thus the rate of LUCC decreases.

By associating driving forces to LUCC different influences at the regional level were observed, namely LUCC into agriculture land derived from the construction of dams (Alentejo region), or the conversion of coniferous forest into eucalypt forest (Centre region) associated with increased gross value added (GVA) and employment in industry and forestry. Temporal differentiation of LUCC driving forces was also observed, particularly in the settlement expansion between 1995 and 2007 due to the construction of large infrastructures (e.g., highways, industrial complexes, or buildings), which is reflected on employment in industry and construction and respective GVA. However, certain LUCC have implications, particularly in energy consumption, for which different behavior between regions can be highlighted in this analysis.

It was also observed that certain LUCC have multiple driving forces of economic and social nature, like for instance the LUCC for settlements associated with employment (agriculture, forestry and industry), agricultural production (e.g., wine) and gross value added. The increase in irrigated crops was driven by the construction of dams, but also presents a strong correlation with the employment in the agricultural sector and the volume of exports. The implications associated with the analyzed LUCC highlights the consumption of electric energy. The increase of vineyards has been reflected in larger volume of exports to meet the increased demand for Portuguese wine products in recent years, according to the Portuguese Wine Institute (IVV). Because of these reasons, the soil conversion of these plantations was promoted and its expansion took place in different regions.

The driving forces of LUCC are very diverse depending on the territory. For example, in Cimandiri and Cibuni Watersheds (Java Island), Kelarestaghi and Jeloudar [79] highlighted the rainfall, soil type, slope, population, population density, and distance to urban areas as the most important variables for the LUCC (1978–2012); in northern Iran, in addition to the variables above mentioned, Aroengbinang [88] also highlighted the distance from drainage network; and, in Alt Emporda county (northeast of Spain), Serra et al. [42] referred to economic factors (e.g., agricultural subsidies) to promote irrigate crops versus dry crops, or social factors (e.g., senior agrarian holders) to justify the cultivated areas reduction. In Portugal, where the forest and agricultural land predominates, these LUCC driving forces also are important, i.e., the allocation of subsidies (to forest and agriculture), agricultural abandonment due to social and economic factors (e.g., low wages, emigration of the population, poor agricultural and forestry production, reduced competitiveness in Portuguese and international markets, etc.), the construction of large infrastructures such as dams, among other factors. In Ribeiro et al. [77] already referred to some of these factors as driving forces boosters of LUCC in Portugal (regional level), especially in agricultural land.

The landscape is the identity of a territory and it contributes to human well-being promoting important cultural, ecological, environmental and social functions [89]. In this context, landscape should be the target of constant evaluations due to political, socioeconomic and territorial decisions that are taken at the macro scale (e.g., distribution of social funds and agricultural development strategies and guidelines for the regional territory) with direct implications in LUC and natural ecosystems. Portugal has benefited from European Union (EU) funds for agricultural, forestry, transportation infrastructure, among others, allowing the development of large projects that culminated in LUCC in very large areas, especially in the Alentejo region [90,91]. In this sense, the results presented are important to estimate the potential implication of economic decisions to the economical (corporations and state) and political strategy to develop profitable economic sectors (e.g., *Eucalyptus* forest, vineyards, olive trees, rice crops). These decisions have inevitable consequences on the employment, electricity and energy consumption, volume of exports and gross value added. In addition, studies about the driving forces that control LUCC and possible implications on society, economy, environment and territory are important to the implementation of new land management guidelines and develop more effective strategies for ecosystems protection [92].

This research also shows that the LUCC projections are a challenging task because they involve several dynamic factors that can affect the LUCC in short periods. In addition, the example of the Alqueva dam construction caused deep LUCC in a short period, which would not have been predicted in a projection made with the 1995 LUC data.

The obtained results are also important to the LUC sustainability of the Portuguese territory, because the forest ecosystems have been continuously degraded by forest fires and human activities (e.g., disforestation). The forest surrounding the principal urban areas has diminished in each decade and the ecological pressure in these areas is high.

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Modeling the Probability of Surface Artificialization in Zêzere Watershed (Portugal) Using Environmental Data

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Abstract: The land use and land cover (LUC) of the Zêzere watershed (Portugal) have undergone major changes in recent decades, with the increase of artificial surfaces. This trend is quantified in some studies, but the probability of the increase of this type of LUC, nor the places where the next transitions or land use/cover changes (LUCC) for artificial surfaces will have high probability of occurrence has not yet been assessed. This research presents an evaluation of these two aspects, by means of bivariate statistical models (fuzzy logic and information value) and environmental data. The artificialization probability by sectors within the same watershed is also evaluated, to further understand which areas will require greater attention, taking into account the environmental conditions favorable to the occurrence of this process and bearing in mind the conditions under which this process took place in the past. The results obtained using these models were assessed independently, through curves of success, noting that the modeling through the fuzzy gamma presents slightly better efficiency in determining the probability of artificialization surfaces in the study area. The area with the highest probability of artificialization is mostly located in the SW of this watershed, but high probabilities are also present in the upstream sector, being those areas that require further preventive measures once they have influence on the water quality and quantity in the main reservoirs of this watershed.

Keywords: LUC; LUCC; artificial surfaces; fuzzy logic; information value; spatial analysis; water quality

1. The Artificialization of Surfaces and Their Assessment

Urban growth has been evaluated in different territories around the world, considering the spatiotemporal aspect, as well as the factors that induced it [1–6]. Other studies have emerged in the context of land use and land cover changes (LUCC) to assess where the soils are being converted into artificial surfaces [7–11], especially when there is loss of soils essential for the development of agricultural practices, or the conversion of forest areas. These processes have multiple socio-economic and environmental impacts [12–16]. In this sense, the determination of driving forces (socio-economic, environmental, or other) that are the cause of LUCC is fundamental to understand the factors that induced them and for the creation of measures aimed at the sustainability of land use [15,17]. Some studies demonstrating the links between driving forces and LUCC have appeared recently, also quantifying how much each factor represents to the observed changes [13,18–22].

In Portugal, studies addressed the impacts of LUCC in the environment, in particular the major transitions of land use and land cover (LUC) resulting from deforestation and their contribution to emissions and removals of CO_2 [23], or in water bodies [17,24,25].

The evaluation of disturbances caused by LUCC in water availability (quantity and quality) are also essential for a sound land use planning [17], particularly in places where there was already degradation of this natural resource by the occurrence of certain harmful events, e.g., forest fires [26].

Urban growth can be considered a negative factor on water availability, particularly where this causes water stress [17]. In this context it is desirable to minimize the artificialization in the neighborhood of important water reservoirs used to supply the populations and their activities, namely within the influence area of water catchment towers.

The artificialization of surfaces has been quantified in the Portuguese territory based on cartography produced in recent years (LUC maps of Portugal, Landyn maps, and CORINE Land Cover—CLC). Data consistency increased a great deal with the most recently reviewed and published datasets [8,27,28].

However, so far there are no estimates of the possible increase in this type of LUC (in area), or the soils which will most likely be occupied or suffer LUCC for this type of LUC. In hydrographic basins the increase of this type of LUC has negative impacts, especially in the increase of surface runoff and also in the increase of physical and chemical substances of anthropic origin that are drained to the water bodies, causing their degradation [17].

The evaluation of urban growth has been based on methodologies using Geographic Information Systems (GIS) and remote sensing tools for the assessment of LUCC [1,3,5,29]. These tools for the collection, processing, and analysis of geographic information (GI) allow more detailed analysis of LUCC and the monitoring of natural or anthropogenic processes [30] that occur in the territories (e.g., artificialization surfaces).

For the evaluation of the LUCC, different methodologies have been used, especially the cellular automata model and artificial neural networks, with good results in the estimation and representation of land cover dynamics [6,31–34]. In the estimation of future LUCC, the probabilistic cellular automata-Markov model has been used in several studies [6,35–38].

Many studies have determined the probability of occurrence of a phenomenon in the future (e.g., landslides, risk of forest fire, floods, etc.) [39–42] based on the conditions observed in the past that caused certain phenomena in a certain place. These methodologies have a strong statistical component, differing only in the integration of the respective variables and method of calculation (e.g., bivariate methods and logistic regression). These factors can provide different results and, consequently, different interpretations. Thus, the methods used for the validation of results are essential to understand what is the best method for modeling a given phenomenon [42].

Some methodologies for validating results have emerged, including the modeling of the probability of occurrence of a natural phenomenon with verified occurrences and, thus, allowing the verification of the final results (through the intersection of GI) if the same occurrences fall on the areas with the highest probability of occurrence. Another option is to use part of the dependent variable for modeling and another part to validate the results obtained (random partition). These methods allow the development of success or prediction curves [43] and receiver operating characteristic (ROC) [44,45], and to quantify their robustness for modeling.

2. Main Objectives

This research aims to test two bivariate statistical models for the identification of areas with higher probability of surface artificialization in the Zêzere watershed (Portugal), bearing in mind the increase verified in the last two decades.

The information used is essentially environment-related data, once we considered in this study that socio-economic conditions remain constant, so this information was not part of the model.

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The validation of results will take place with information of LUC, namely information about artificial surfaces for two different times: 1990 and 2012. The information of the first year will be used to determine the areas with highest probability of artificialization and the information of the last year will serve to validate the results. We also considered an intermediate date (2000) for verification of the probability of surface artificialization, obtained with data from 1990, being that this data is complementary for the assessment of the validation performed with 2012 data.

Another goal of this study is to determine the differences between the two models in different locations (sectors) within the watershed, in order to quantify and understand the differences between all sectors. Special attention is taken in assessing which are the most important independent variables for determining the probability of artificialization for this territory.

3. Research Area

The study area is the Zêzere watershed (Portugal) (Figure 1). This watershed has an area of 502,278.4 ha, and includes one of the main drinking water reservoirs (Castelo de Bode) in Continental Portugal. The surface artificialization in 1990 was approximately 1.2% of the total area of the watershed, but in the last two decades it has increased approximately 0.5% (according to data from CLC of 1990 and 2012), especially in the vicinity of water bodies. This factor can induce water stress within this watershed, namely decreasing water quality and increasing water treatment costs [17,46].

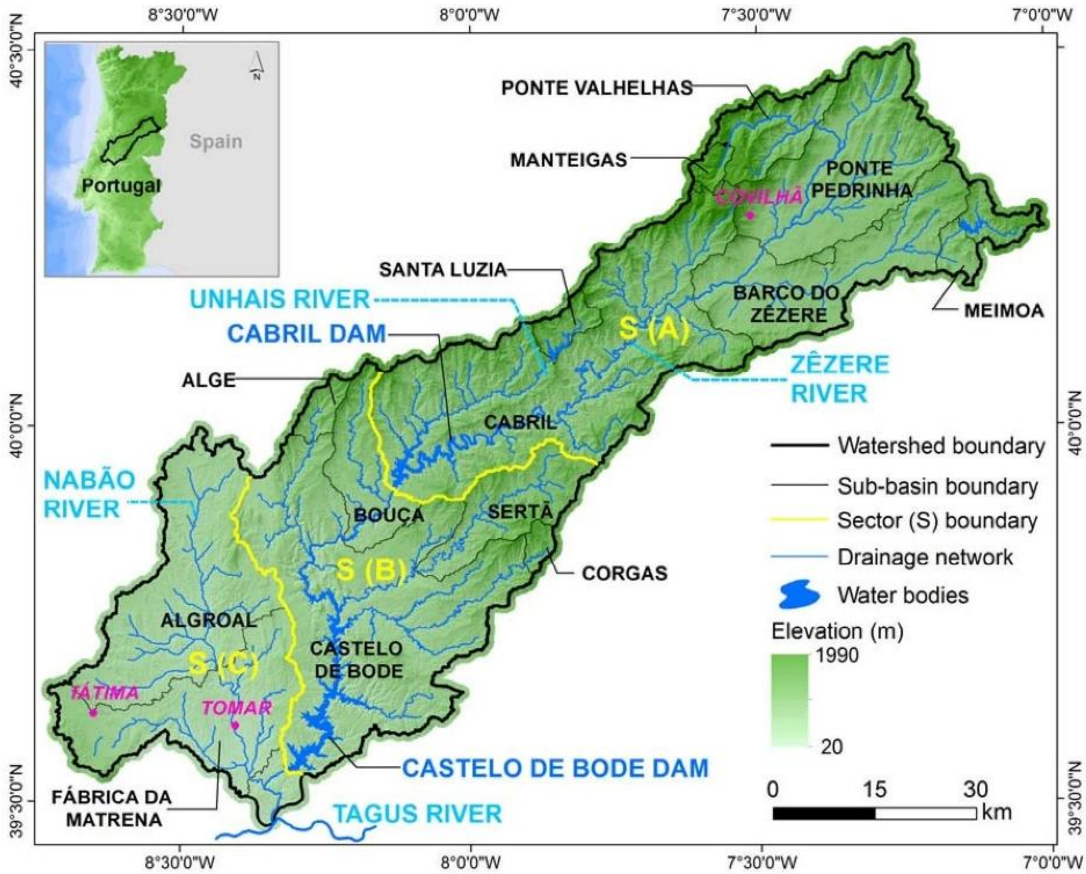

Figure 1. Zêzere watershed (study area).

The watershed was divided into three sectors (Figure 1): two of them based on the location of the main reservoirs (A and B) and one based on the sub-basins without reservoirs (C). The objective of this division areas is to assess the differences in the probability of artificialization: initially within the watershed, considered as a whole, with the selected statistical models, and later to evaluate and differentiate, spatially, this probability between the different watershed sectors and their behavior when compared to the whole watershed results.

In this watershed, since 1990, the artificial surfaces areas increased, particularly in the sub-class discontinuous urban fabric (Table 1). This increase in dispersed artificial surfaces carries greater economic and financial burden, associated in particular with the construction of basic infrastructures (roads, sewage systems, drinking water, power supply, etc.). Here there are also records of environmental disturbances, particularly at the level of domestic waste and water treatment, confirming a deficiency in this area.

Table 1. Areas occupied by artificial surfaces (%) in the Zêzere watershed, from 1990 to 2012.

LUC	1990	2000	2006	2012
Continuous urban fabric	0.02	0.02	0.02	0.02
Discontinuous urban fabric	1.01	1.13	1.15	1.32
Industrial or commercial units	0.06	0.16	0.25	0.24
Road and rail networks and associated land	0.00	0.00	0.01	0.01
Airports	0.01	0.01	0.01	0.03
Mineral extraction sites	0.03	0.05	0.06	0.06
Dump sites	0.01	0.01	0.02	0.03
Construction sites	0.04	0.05	0.01	0.00
Sport and leisure facilities	0.01	0.01	0.01	0.01

In the watershed upstream sector (A) it is located the Estrela mountain (Serra da Estrela). Here the hillsides with slopes exceeding 20% are one of the constraints to urbanization and, thus, the location of major cities and towns is primarily in locations with lower altitude and reduced slope. The Cabril dam is located in this sector of the watershed; an important infrastructure for public water supply.

Sector B comprises the Castelo de Bode reservoir, this area being mainly occupied by scrub and/or herbaceous vegetation associations, resulting mainly from large forest transitions that occurred between 1990 and 2012. This sector also comprises hillsides with slopes exceeding 20%.

The geomorphology of the downstream sector (Sector C) is totally different from the upstream sectors, i.e., the relief is more flat, and was one of the factors that facilitated the urban settlement (e.g., Tomar City). This sector is also characterized by other factors, such as soil characteristics, favorable to the development of agricultural practices, high sun exposure, higher temperature, proximity to water courses, and proximity to railways connecting the area with larger urban areas, like Lisbon, among others. Nevertheless, this is the most relevant sector within the Zêzere watershed once it includes the most relevant water catchment within the Portuguese drinking water supply infrastructure.

The artificial surfaces increase at this watershed occurred in areas very close to the major urban centers within the watershed (Tomar, Fátima, and Covilhã). The analysis of the geographical dispersion of the artificial surfaces (from data of the CLC) found that the new areas have emerged as the expansion of existing ones, particularly on the periphery of the main larger conurbations (Figure 2). It was also found that the largest increase in artificial surfaces occurred until the year 2000, within less than 5 km of the urban centers previously referred.

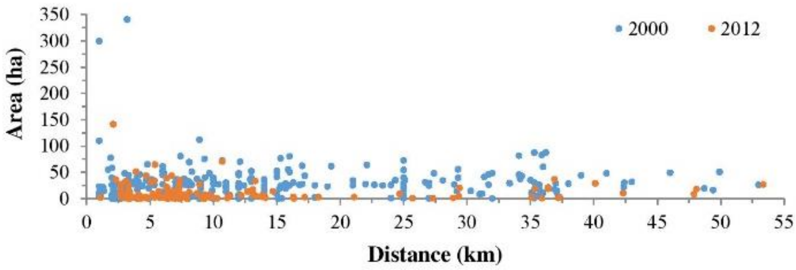

Figure 2. Dispersion of new artificial surfaces. Relation between the distance of centroids of these surfaces (2000 and 2012) to principal urban centers (Tomar, Fátima and Covilhã).

4. Data, Tools, and Methods

4.1. Statistical Methods and Validation

The areas with higher probability of artificialization were determined using fuzzy logic [47] and information value [48] methods. This last methodology was adapted to the study of surface artificialization probability. In these methods it is assumed that a particular phenomenon that occurred in a given territory has a probability to happen in the future under the same conditions under which it occurred in the past [42,49–51].

For the determination of information value, first we calculated a priori and conditional probabilities. This methodology was presented in Meneses and Zêzere et al. [42,52]. After calculating these probabilities, we used the following equation to determine the information value [48]:

$$I_i = Ln \frac{CPji}{Pp} \tag{1}$$

In Equation (1), I_i is the information value; $CPji$ is the conditional probability of surface artificialization on class i of the thematic map j; and Pp is the a priori probability of occurrence of surface artificialization.

In assessing the final probability of surfaces artificialization, i.e., integrate information values of all independent variables, we considered the following equation:

$$I_j = \sum_{i=0}^{n} X_{ij} I_i \tag{2}$$

In Equation (2), I_j is the total information value of pixel j, I_i is the information value of each pixel of each independent variable, n is the number of variables, X_{ij} assumes the value 1 or 0 depending on the presence or not of the variable in the field unit.

The fuzzy logic methodology, developed by Zadeh [53], admits the variation between 0 and 1 (or 0 and 100%) of an existing element in a given set, this being expressed by a fuzzy membership value. According to Bonham-Carter [47], the assignment of values of fuzzy membership to every variable is typically made from the subjective evaluation (expert opinion) of their importance in the model, so it is considered an heuristic method. However, in this study, the fuzzy membership values were assigned objectively to each class of independent variables, i.e., its importance was calculated in proportion to each calculated conditional probability. The maximum value of all of the independent variables was determined and, from this, for each class, the respective fuzzy membership value was calculated as the result of dividing the respective conditional probability by the maximum value found earlier.

Among the various operators for combining fuzzy membership values, we used the fuzzy gamma operator, because this combines two operators [47]: sum and algebraic product. The Fuzzy gamma operator uses the following equation [47]:

$$Fuzzy\ Gamma = \left(1 - \prod_{i=1}^{n}(1-\mu_i)\right)^{y}\left(\prod_{i=1}^{n}\mu_i\right)^{1-y} \quad (3)$$

In Equation (3), μ_i is the fuzzy association values (i = 1, 2, 3, ... , n) for the variables 1, 2, 3, ... , n; n corresponds to the number of variables considered, and y the parameter set by the operator.

The geographic information of the artificial surfaces considered in this study is the result of the CLC for the years 1990 and 2012 (level 2), comprising approximately 5978 and 8588 ha, respectively. The GI of the first year (dependent variable) was used for modeling with the methods presented earlier; and the GI for the last year was used for validation of the results, considering in this procedure only the artificial surfaces that have emerged between the two years (approximately 2610 ha). By applying this procedure, we want to know if the artificial surfaces of 2012 coincide with the areas with the highest probability of artificialization obtained by the models previously described.

The process used for the validation of results included the elaboration of success curves and the measurement of the area under the curve (AUC), according to the methodology described by Meneses [42] and Tehrany et al. [43]. This method of validation enables the evaluation of the robustness of the models presented for the determination of artificial surfaces probabilities.

In the analysis of the results the sectors A, B, and C (Figure 1) were distinguished in order to determine the possible differences between the results of the two models on the probability of artificialization surface within the same watershed.

The importance of each independent variable in the process of artificialization for each sector was also determined, in order to understand what the spatial influence of each predisposition factor in the development of this process is. In this procedure the accountability (A_I) and reliability (R_I) indexes [42,54] were determined using Equations (4) and (5). A_I explains how various classes of predisposition factors are relevant in the analysis because they contain artificial surfaces, while R_I depends on the average density of artificial surfaces in classes of predisposition factors most relevant to the development of this process.

$$A_I = \frac{\sum_{i=1}^{n} k}{N}100 \quad (4)$$

$$R_I = \frac{\sum_{i=1}^{n} k}{\sum_{i=1}^{n} y}100 \quad (5)$$

In Equations (4) and (5), A_I is the accountability index; R_I is the reliability index; k is the area of artificial surfaces in classes with values of conditioned probabilities superior to a priori probabilities; N is the total area of artificial surfaces; y the area of each class of independent variable with conditioned probability above the a priori probability.

4.2. Data Collection and Tools

The GI themes considered in this research are diversified (Figure 3). Cartography of the Portuguese Environment Agency (soil maps, insolation, humidity, temperature, and precipitation), available online, was used. The LULC considered is the CLC data produced by the Portuguese General Directorate for Territorial Development. Due to the similarity between the spatial geological units and the soil types, we opted to use only this last variable.

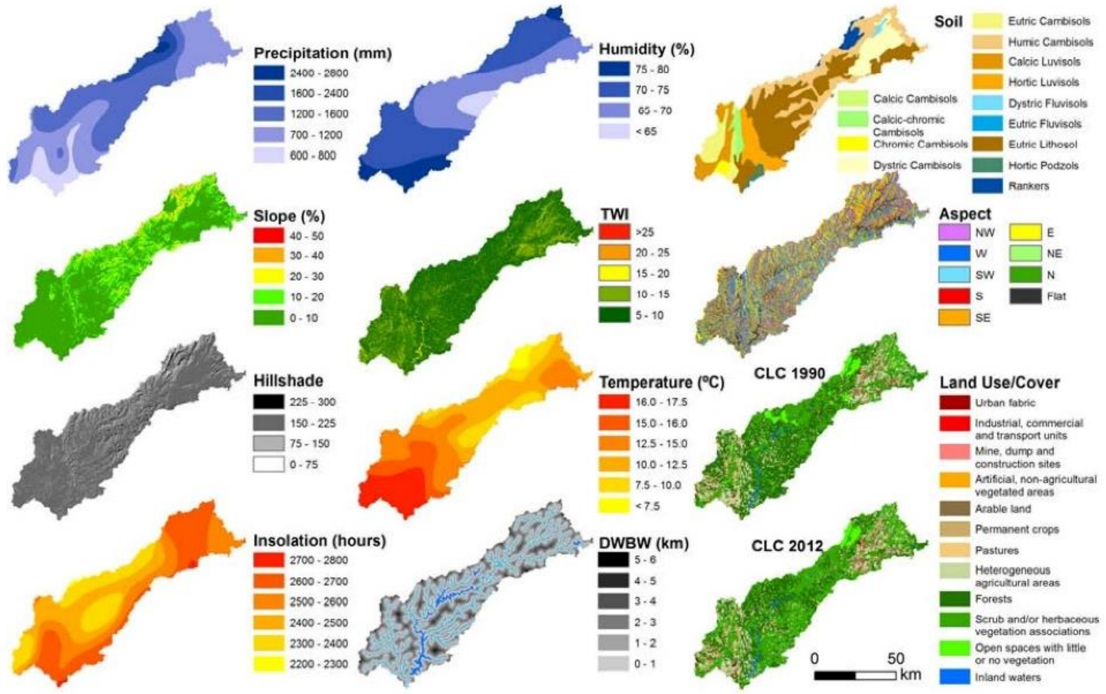

Figure 3. Independent variables used in modeling artificial surfaces and LUC (CLC) in the years 1990 and 2012.

Variables derived from the Digital Elevation Model (DEM) from the GMES RDA project (EU-DEM) made available by the European Environment Agency, were also used, in particular the slope, aspect, and hillshade. These variables derived from the DEM also calculated the topographic wetness index—TWI [55].

In addition to this GI, the distance to water bodies and watercourses (DWBW) was also obtained, to assess the influence of their location on the surface artificialization that occurred over the last two decades, since the vicinity of the main reservoirs in the Zêzere watershed [46] was subject to an increase in housing developments.

All collected GI was harmonized and manipulated in the Geographic Information Systems (GIS), using the software ArcGIS 10.2 and ILWIS 3.4. The GI of the variables in vector structure was converted to raster (pixel 10×10 m) for carrying out the various processing procedures. The selection of this resolution was the result of several geoinformation conversion tests, where different modeling resolutions were tested in this research, and it was found that the results of the adopted resolution are similar to those obtained using data with higher resolution. After several vector-to-raster conversions, the resolution considered is the one that allows better results in the determination of artificialization probabilities, since the surface loses a lot of information in the process of generalization that occurs during data conversion, in particular in the conversion of LUC, where small buildings were not considered in the modeling due to the pixel size (e.g., $20 \text{ m} \times 20 \text{ m} = 400 \text{ m}^2$), and some of the buildings that appeared during the period under evaluation are also not included in the validation process.

For the intersection of the variables presented in Figure 3 we used only ArcGIS 10.2. This software was also used for determining the areas with greater probability of artificialization. On the fuzzification of fuzzy membership values we used the Spatial Data Modeler (ArcSDM), module added to ArcGIS 10.2.

In order to verify that the artificialization surface probabilities obtained from the year 1990 (CLC data) have sequences 10 years later, we also calculated the probabilities for the year 2000. With these results we intended to check the correspondence between the two years (similar odds for the same class of independent variables) so as to enhance the use of the information of 2012 in the context of the models adopted.

5. Results and Analyses

5.1. Conditioned Probabilities of Artificialization Surfaces in the Zêzere Watershed

Each class of independent variables considered in this study presents a different probability of surface artificialization (Table 2). The flat surfaces are those that have a higher probability (higher conditional probabilities) in the variable Aspect, a fact confirmed also in the variable Slope (greater in weak slopes); for hillshade, with records varying between 0 and 300, the most influential is the class 150–200; also with high probability are the surfaces with higher humidity, insolation, and temperature. The distance to water bodies and watercourses is also one factor that conditions the surface artificialization, where the 4–5 km buffer in DWBW has the highest probability (*CPji* AS 1990 in Table 2), due to the total artificial surface included in it. However, the artificial surface is high along water courses (up to 1 km vicinity), revealing a pattern in the preference for these surfaces for the location of infrastructures (housing, industrial complexes, etc.). The Topographic Wetness Index (TWI) reveals that the surfaces with lower values are the ones that have less probability of artificialization.

For calculating the information value, the a priori probability (probability to find artificial surfaces) should be also calculated, which is 0.012. This value results from the division of the total area of artificial surfaces by the total area of each independent variable.

The relationship (coefficient of determination—R^2) between the conditional probabilities obtained from information of artificial surfaces of 1990/2000 is high for most independent variables (Figure 4), with the exception of DWBW, where it was observed a significant increase of artificial surfaces in more distant areas to water bodies and watercourses in the year 2000, given the area occupied by artificial surfaces in 1990. The R^2 between the conditional probabilities of 1990/2012 is also high, with some variables with lower R^2 compared to 1990/2000, such as the Insulation and TWI, but the DWBW highlights with a higher R^2, indicating the greater probability of artificialization in the vicinity of water bodies.

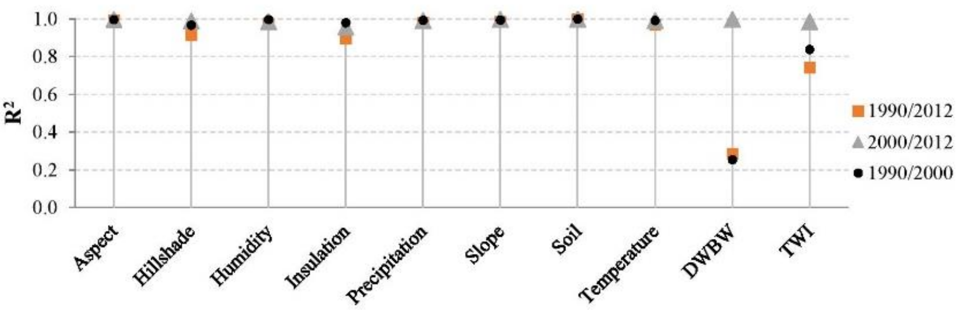

Figure 4. R^2 resulting between conditioned probabilities of artificial surfaces of 1990/2000, 2000/2012, and the total period (1990/2012).

Considering the conditional probabilities of 1990/2000, 2000/2012, and 1990/2012 of all independent variables it was verified that a high correspondence between the results was obtained (R^2 = 0.994, 0.999 and 0.992, respectively).

Table 2. Area of artificial surfaces (AS), conditional probability (*CPji*), information value (IV), and fuzzy membership value (FM) for each class of the independent variables, in the Zêzere watershed.

Variables	Classes	Total Area (ha)	AS 1990 (ha)	AS 2000 (ha)	AS 2012 (ha)	*CPji* (AS 1990)	*CPji* (AS 2000)	*CPji* (AS 2012)	IV (AS 1990)	FM (AS 1990)
Aspect	Northwest	51,549.15	338.96	409.33	482.17	0.007	0.008	0.009	−0.593	0.007
	West	56,574.22	411.9	489.83	549.45	0.007	0.009	0.010	−0.491	0.008
	Southwest	61,918.88	705.13	848.98	967.34	0.011	0.014	0.016	−0.044	0.013
	South	57,996.57	884.72	1050.81	1209.06	0.015	0.018	0.021	0.248	0.017
	Southeast	61,927.05	786.6	953.71	1138.82	0.013	0.015	0.018	0.065	0.014
	East	54,624.12	642.44	787.59	961.53	0.012	0.014	0.018	−0.012	0.013
	Northeast	48,357.44	525.06	657.68	791.94	0.011	0.014	0.016	−0.092	0.012
	North	42,475.03	300.68	379.59	458.83	0.007	0.009	0.011	−0.52	0.008
	Flat	66,855.89	1382.43	1682.28	2028.42	0.021	0.025	0.030	0.552	0.023
Hillshade	250–300	221.62	3.30	3.15	3.15	0.015	0.014	0.014	0.224	0.016
	200–250	89,250.44	259.45	314.87	352.12	0.003	0.004	0.004	−1410	0.003
	150–200	306,686.8	5193.93	6328.9	7562	0.017	0.021	0.025	0.353	0.019
	100–150	85,814.72	475.65	559.81	614.41	0.006	0.007	0.007	−0.764	0.006
	50–100	18,890.39	43.41	50.54	53.17	0.002	0.003	0.003	−1645	0.003
	0–50	1414.38	2.18	2.53	2.71	0.002	0.002	0.002	−2044	0.002
Humidity (%)	75–80	59,071.72	1432.73	1775.39	2442.13	0.024	0.030	0.041	0.712	0.027
	70–75	249,233.66	3745.74	4436.33	5012.9	0.015	0.018	0.020	0.233	0.017
	65–70	171,005.31	745.06	993.69	1051.27	0.004	0.006	0.006	−1005	0.005
	<65	22,967.66	54.39	54.39	81.26	0.002	0.002	0.004	−1615	0.003
Insolation (Hours)	2700–2800	4373.7	74.95	83.46	83.46	0.017	0.019	0.019	0.365	0.019
	2600–2700	149,922.62	2085.83	2603.91	3409.02	0.014	0.017	0.023	0.156	0.015
	2500–2600	123,480.1	919.68	986.32	1051.59	0.007	0.008	0.009	−0.469	0.008
	2400–2500	117,329.61	1419.26	1629.11	1747.50	0.012	0.014	0.015	0.016	0.013
	2300–2400	105,098.18	1478.2	1957.00	2295.99	0.014	0.019	0.022	0.167	0.015
	2200–2300	2074.14	0	0	0	0	0	0	**−0.469** *	0
Precipitation (mm)	2400–2800	5012.81	35.06	35.06	35.06	0.007	0.007	0.007	−0.532	0.008
	2000–2400	10,286.57	132.26	132.26	131.62	0.013	0.013	0.013	0.077	0.014
	1600–2000	20,541.19	430.63	506.08	531.68	0.021	0.025	0.026	0.566	0.023
	1400–1600	66,379.08	550.95	769.49	916.67	0.008	0.012	0.014	−0.36	0.009
	1200–1400	132,983.26	1623.23	2009.96	2402.33	0.012	0.015	0.018	0.025	0.013
	1000–1200	90,577.8	945.34	1115.63	1311.52	0.01	0.012	0.014	−0.131	0.011
	800–1000	130,193.4	1226.4	1474.78	1642.62	0.009	0.011	0.013	−0.234	0.01
	700–800	39,288.9	677.81	804.97	1048.72	0.017	0.020	0.027	0.371	0.019
	600–700	7015.34	356.24	411.57	567.34	0.051	0.059	0.081	1,451	0.056

Table 2. *Cont.*

Variables	Classes	Total Area (ha)	AS 1990 (ha)	AS 2000 (ha)	AS 2012 (ha)	*CPji* (AS 1990)	*CPji* (AS 2000)	*CPji* (AS 2012)	IV (AS 1990)	FM (AS 1990)
Slope (%)	40–45	175	0	0	0	0	0	0	**−0.967** *	0
	35–40	874.97	0	0	0	0	0	0	**−0.967** *	0
	30–35	2670.4	1.35	1.35	1.35	0.001	0.001	0.001	−3159	0.001
	25–30	7100.77	33.55	33.55	33.55	0.005	0.005	0.005	−0.924	0.005
	20–25	16,322.43	61.62	73.16	72.73	0.004	0.004	0.004	−1148	0.004
	15–20	37,573.66	264.08	276.15	290.43	0.007	0.007	0.008	−0.527	0.008
	10–15	79,761.58	360.91	421.9	439.29	0.005	0.005	0.006	−0.967	0.005
	5–10	156,451.83	1267.97	1596.84	1863.89	0.008	0.010	0.012	−0.384	0.009
	0–5	201,347.71	3988.44	4856.85	5886.32	0.020	0.024	0.029	0.509	0.022
Soil	Humic Cambisols	110,548.72	708.37	800.85	819.07	0.006	0.007	0.007	−0.619	0.007
	Rankers	12,992.15	31.48	31.48	31.48	0.002	0.002	0.002	−1592	0.003
	Dystric Cambisols	48,878.67	581.17	829.4	1067.76	0.012	0.017	0.022	−0.001	0.013
	Dystric Fluvisols	3017.1	6.39	6.39	6.39	0.002	0.002	0.002	−1726	0.002
	Eutric Lithosol	187,479.93	1475.36	1776.12	2140.97	0.008	0.009	0.011	−0.414	0.009
	Calcic Cambisols	8275.49	77.74	86.98	86.98	0.009	0.011	0.011	−0.237	0.01
	Calcic Luvisols	34,032.09	1300.16	1509.65	1793.44	0.038	0.044	0.053	1166	0.042
	Hortic Luvisols	40,991.55	320.14	376.3	421.69	0.008	0.009	0.010	−0.421	0.009
	Calcic-chromic Cambisols	13,019.96	169.54	215.53	215.55	0.013	0.017	0.017	0.09	0.014
	Eutric Cambisols	30,585.64	1213.24	1512.2	1792.56	0.04	0.049	0.059	1204	0.044
	Chromic Cambisols	6065.93	80.23	100.8	197.57	0.013	0.017	0.033	0.106	0.015
	Hortic Podzols	6390.79	13.8	13.77	13.77	0.002	0.002	0.002	−1707	0.002
	Eutric Fluvisols	0.33	0.3	0.33	0.33	0.909	1.000	1.000	4336	1000

Table 2. *Cont.*

Variables	Classes	Total Area (ha)	AS 1990 (ha)	AS 2000 (ha)	AS 2012 (ha)	*CPji* (AS 1990)	*CPji* (AS 2000)	*CPji* (AS 2012)	IV (AS 1990)	FM (AS 1990)
Temperature (°C)	16.0–17.5	83,699.31	2360.49	2918.1	3851.4	0.028	0.035	0.046	0.863	0.031
	15.0–16.0	60,518.29	819.04	918.61	929.71	0.014	0.015	0.015	0.129	0.015
	12.5–15.0	135,430.82	977.72	1250.24	1320.63	0.007	0.009	0.010	−0.5	0.008
	10.0–12.5	135,296.25	814.51	994.85	1122.5	0.006	0.007	0.008	−0.682	0.007
	7.5–10.0	72,973.84	935.96	1094.53	1279.85	0.013	0.015	0.018	0.075	0.014
	<7.5	14,359.84	70.2	83.47	83.47	0.005	0.006	0.006	−0.89	0.005
DWBW (km)	5–6	135.23	1.26	11.52	11.52	0.009	0.085	0.085	−0.245	0.01
	4–5	2872.22	140.47	226.48	236.48	0.049	0.079	0.082	1413	0.054
	3–4	24,827.85	458.91	563.72	676.75	0.018	0.023	0.027	0.44	0.02
	2–3	80,622.99	1053.36	1258.36	1404.17	0.013	0.016	0.017	0.093	0.014
	1–2	154,963.46	1443.75	1803.56	2327.76	0.009	0.012	0.015	−0.245	0.01
	0–1	238,856.6	2880.17	3396.16	3930.88	0.012	0.014	0.016	0.013	0.013
TWI	>25	910.24	12.52	10.48	10.43	0.014	0.012	0.011	0.145	0.015
	20–25	2612.17	43.22	47.5	53.52	0.017	0.018	0.020	0.33	0.018
	15–20	18,209.96	297.73	348.24	401.76	0.016	0.019	0.022	0.318	0.018
	10–15	174,288.6	3317.83	4030.44	4772.98	0.019	0.023	0.027	0.47	0.021
	5–10	306,257.38	2306.62	2818.86	3342.93	0.008	0.009	0.011	−0.457	0.008

Note: * These values correspond to the smaller IV observed in the variable under analysis.

5.2. Spatial Variation of the Probability of Artificialization Surfaces in the Zêzere Watershed

The artificialization surface probability is higher in the downstream sector of the watershed, as shown by the maps resulting from application of statistical methods described above (Figure 5).

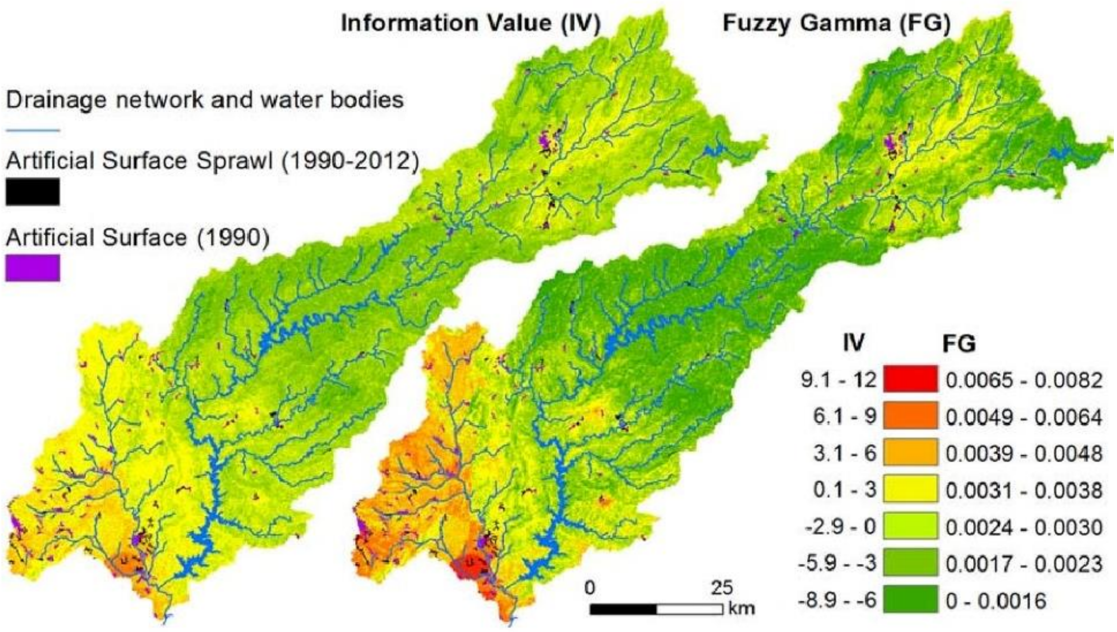

Figure 5. Artificialization surface probability determined by information value and fuzzy gamma, with artificial surfaces from 1990 (the classification of this map follows the method of natural breakdown).

The map with the results of information value shows the sectors upstream and downstream of the watershed, especially this last one, with a high probability of artificialization surface.

The map with the results of the fuzzy gamma operator shows the highest probability in the vicinity of the main water lines in the southwest of the Nabão River, but also shows that the central areas in the upstream sector have some probability of artificialization surface.

The success curve characterizes the quality of a forecast system by describing the system's ability to correctly anticipate the development or non-development of a predefined event [56,57]. In this case, the predefined event is the artificialization of the surfaces in the Zêzere watershed, and the probability of artificialization obtained was validated with the artificial surfaces that have emerged up to 2012. During the validation of results it was found that both models have similar robustness for the determination of artificial surfaces probabilities, as noted through with success rate curves (Figure 6). With around 35% of total area of the watershed classified in descending order of probability of artificialization, about 80% of the artificial surfaces of 2012 are validated, and with about 50% validated, 90% of the total artificialized area (Figure 6). However, modeling using a fuzzy gamma operator presented slightly better results, with AUC of 79.4%, compared to the AUC of 79.1% obtained by the information value.

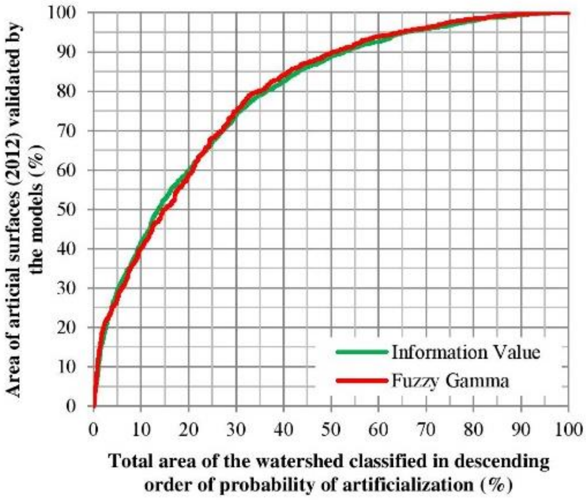

Figure 6. Success rate curve for the statistical models used in the determination of artificial surface probabilities.

5.3. Artificialization Surfaces by the Sectors of the Zêzere Watershed and the Relevance of the Environmental Predisposing Factors to Artificialization Process

The surface artificialization probability is highly variable, spatially, depending on the conditions existing in the territory. The statistical results presented in Table 3 demonstrate high variability of artificialization probability between the sectors defined in the watershed, showing areas A and B with the minimum values, and sector C with maximum probability of artificialization.

Table 3. Statistical description of information value (IV) and fuzzy gamma (FG) by sectors (S) of the Zêzere watershed (significance level $p < 0.05$).

Description	IV			FG		
	S (A)	S (B)	S (C)	S (A)	S (B)	S (C)
Min.	−8.89	−8.89	−4.49	0	0	0.0014
Max.	3.34	4.25	10.41	0.0051	0.0067	0.0082
Mean	−2.58	−1.67	1.88	0.0020	0.0023	0.0041
Std. Dev.	1.84	1.98	1.86	0.0007	0.0008	0.0011

In order to assess the artificialization probability it is also important to know which environmental predisposition factors are the most important. Thus, the accountability and reliability index for each sector of the Zêzere watershed were determined, where the three most relevant predisposition factors in the analysis are highlighted because they contain artificial surfaces in the year 1990 (bold values in Table 4).

The slope turned out to be a very important factor for the artificialization in the three sectors, mainly because of the high area of artificial surfaces in the smaller slope classes. Hillshade is also an important predisposing factor, particularly in sectors B and C. Once sector A includes areas of higher altitude and with a more rugged relief, the humidity and the insolation are the most important factors for the artificialization in this sector; however, the average density of artificial surfaces in each precipitation class is also important considering the set of predisposition factors.

In sector B the temperature has an important influence on surface artificialization, but an analysis of the medium density of artificial surfaces for each independent variable in this sector shows the importance of the type of soils, in particular the Calcic luvisols, where the main drinking water reserves are located.

The C sector soil is also important, considering the high artificialization that occurred in certain classes, but the insolation is an important factor in the analysis of the average density of artificial surfaces by class.

Table 4. Accountability (A_I) and reliability (R_I) indexes by sectors (S) of the Zêzere watershed.

Variables	S (A)		S (B)		S (C)	
	A_I	R_I	A_I	R_I	A_I	R_I
Aspect	59.9	1.0	54.2	0.9	54.5	3.8
Hillshade	72.5	1.1	**91.1**	1.0	**94.6**	3.4
Humidity	**98.5**	1.5	67.5	0.9	44.8	5.0
Insolation	**84.4**	1.5	65.0	1.3	36.8	6.5
Precipitation	44.1	2.2	48.0	1.0	56.4	5.7
Slope	**77.8**	0.9	**69.4**	1.2	**87.2**	3.4
Soil	30.2	1.2	69.3	3.5	**81.3**	3.9
Temperature	47.3	1.6	**86.7**	0.8	74.7	3.6
DWBW	26.9	1.3	54.7	0.8	67.9	3.9
TWI	45.0	1.0	64.2	1.2	70.4	4.0

6. Discussion

The probability of surface artificialization obtained by the information value and fuzzy gamma methods have many similarities in the study area.

These results indicate a good performance of these methods in modeling surface artificialization probabilities, i.e., the artificial surfaces used for modeling (1990) made it possible to differentiate the territory with different probability of artificialization, confirming that a part of these surfaces with a high probability the artificialization occurred (a fact confirmed by overlapping them with the artificial surfaces of 2012). However, it was also found that the new artificial surfaces are located mostly in the periphery of the existing ones, in particular of larger artificial surfaces, which justifies the good performance of the models, i.e., if the expansion occurred mainly from the larger urban centers, it is also more likely that the expansion areas exhibit the same characteristics as the areas of the original urban centers.

The robustness of the methods used has been tested in different studies for determining the susceptibility or probability of occurrence of natural phenomena (e.g., landslides, forest fires, etc.), where the best results have been achieved by the information value model [42]; however, in this research the fuzzy gamma model presented the best performance (Figure 6), although by a marginal difference in relation to the results of the information value model.

The two maps (Figure 5) show that the central sector (B) of the watershed is where there is less probability of artificialization (soils occupied mostly by forest, scrub, and herbaceous vegetation). The natural conditions of this sector are less favorable to human occupation, in particular due to the slope (>25%). This conjugation of less favorable factors to surface artificialization has been referred in some other studies, e.g., Druga and Faltan [58].

The spatial distribution of artificial surfaces in the Zêzere watershed is very uneven throughout the territory and its location is conditioned mostly by the same morphology, this factor being the most important on the distribution of artificial surfaces [58].

The change in the area of artificial surfaces in the Zêzere watershed was evaluated at different times (1990, 2000, 2006, and 2012), which identified the consequences of an increase in the quality of surface water [17,59]. Taking into account the importance of this natural resource and the interference of artificial surfaces in its quality, it is essential to know which areas are those with the greatest artificialization probability in order to avoid new construction, especially in the vicinity of water bodies. These areas are currently experiencing an increase in demand due to the scenic context and watersports, among others [17].

However, in this research it was not proved that the distance to water bodies and watercourses is an important variable in determining the probability of artificial surfaces, because urbanization is still in the process of development in the vicinity of water bodies and infrastructure currently located in these areas is scattered. Additionally, the spatial resolution that characterizes CLC cartography (25 ha) induces limitations to this analysis that require further work. This fact demonstrates the importance of knowledge about the properties of the available GI datasets, and their influence in the results presented in this research that have to be taken into account.

The urban development is also influenced by the location of the main housing clusters [5], which also influence the surface artificialization process, particularly on the periphery of these clusters, where there have been some cases of new housing and infrastructure construction (e.g., roads, railways, industrial complexes, and support equipment, etc.) [3,6]. As a result of this research we highlight the areas with the greatest probability of artificialization (e.g., the SW of sector C), taking into account that under the same environmental conditions which created artificial surfaces in the past, these areas might be artificialized in the future, based on the concept of uniformitarianism implicit in the methodologies used [42,60,61]. Since human intervention was not included in the modeling procedures, and is one of the main agents of LUCC [17,59], some discussion here is justifiable. On the one hand, the application of these variables is impossible, as there are not enough data to demonstrate certain conditions in the past to the watershed under study (e.g., socio-economic power and conditions of the families, infrastructure, or urbanization index, search for housing, or construction of certain infrastructures). On the other hand, there is a very high uncertainty about these human conditions for large periods (next decades), so this approach can only be carried out assuming different kinds of scenarios for the future.

The influence of these man-made factors in the artificialization surface, namely the urbanization in the proximity of road networks, can form the basis of the explanation of the results that are not explained by the models used in this research. However, the option to use only environmental data is due to the fact that the variables used do not present large variations in relatively short periods, such as those considered in this investigation. However, it is acknowledged that this information resulting from anthropic actions is important for determining the areas that will, in the future, become artificial surfaces, but this factor depends only on human actions, such as building new roads or other infrastructure essential to the location of people and goods. Thus, these anthropic actions are encompassed in the process of artificialization and the resulting data are considered artificial surfaces in CLC data.

7. Conclusions

Surfaces artificialization in the Zêzere watershed is more likely to occur in the downstream sector (sub-basin of Nabão River), and this is the place with the highest density of artificial surfaces at present.

The determination of the areas with highest probability of artificialization in the Zêzere watershed, using only environmental data, showed good results, a fact confirmed in the validation (through the curves of success) of the results obtained by the methods of information value and fuzzy gamma.

By comparing the artificialization probability of the sectors delimited in this watershed, it was observed that there is similarity between the results of the two methods obtained for the whole area of the watershed. However, the results differ among sectors, with the highest probability of artificialization in sector C. This spatial differentiation is essential for decision-making in land use planning; in particular, for determining the possible interferences resulting from artificialization in the vicinity of important water bodies to the public water supply. Once there are favorable environmental conditions for this process to occur in these areas, these surfaces present some probability of artificialization. Yet, in this context, it was noted that there are conditions for the increase of the artificialization in the upstream area of the watershed, but the development of this process at this location can be negative in the maintenance of downstream water bodies (water stress). This process leads to important impacts on water quality, mainly due to urban growth in a disorderly manner, and characterized by deficient sewage network systems in the vicinity of the reservoirs.

The spatial differentiation of the artificialization probability will allow better decisions (preventive or reactive) in the territory. In our case it is a watershed with major water bodies in Continental Portugal, and better decisions will contribute to minimize possible consequences resulting from transitions of other types of LUC to artificial surfaces. However, this assessment must include other factors, such as socio-economic conditions [62], restrictions, or obligations set out in territorial and sectorial management plans and programs, along with the chosen strategy to monitor legal framework implementation.

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Capítulo 4

INCÊNDIOS FLORESTAIS EM PORTUGAL CONTINENTAL: DETERMINAÇÃO DE PADRÕES DE USO E OCUPAÇÃO DO SOLO AFETADOS

4.1. INTRODUÇÃO

Os incêndios florestais são um flagelo no território português, pelas mortes e feridos que têm causado ano após ano, e pelas elevadas perdas materiais, onde se incluem habitações, infraestruturas de comércio e industriais, bens agrícolas e florestais, entre outros. Neste sentido, a cartografia de UOS deve ser vista como uma ferramenta essencial para se analisar e perceber espacialmente e temporalmente (utilizando as várias séries cartográficas) a ocorrência dos incêndios florestais.

A cartografia de UOS mais utilizada em Portugal - CLC e COS - apresenta uma classe designada por "Áreas ardidas", mas a área desta classe nem sempre corresponde ao total (ou valor aproximado) da área que efetivamente foi afetada por incêndios florestais. Apresenta-se como exemplo desta discrepância os resultados obtidos no cruzamento entre a CLC 2018 e as áreas ardidas do ano 2017 disponibilizadas pelo Instituto da Conservação da Natureza e das Florestas (ICNF), onde se pode observar que apenas 12,54 % das áreas ardidas no total do ano 2017 tem correspondência com a classe "Áreas ardidas" da CLC 2018, estando a restante área ardida distribuída por outras classes (Tabela 4.1). Sobressai neste exemplo a elevada área ardida inserida nas classes "Espaços florestais degradados, cortes e novas plantações", "Florestas de resinosas" e "Matos" (31,27 %, 13,37 % e 12,13 % da área ardida total, respetivamente). De certa forma, parte destas florestas afetadas por incêndios florestais terão a possibilidade de regenerar naturalmente, mas para este efeito é necessário perceber se as espécies em causa rebentam de toiça, ou se a disponibilidade de sementes permite essa regeneração natural. No caso das espécies de resinosas, após o primeiro incêndio florestal é possível haver regeneração a partir das sementes depositadas nos solos no pós-fogo (estas espécies não rebentam de toiça), mas se num curto período após este incêndio florestal ocorrer outro incêndio perde-se esta possibilidade de regeneração, pois as resinosas em causa ainda não tiveram tempo suficiente para crescer e produzir novas sementes, logo fica em causa a possível regeneração natural destas espécies. Este problema destaca-se em áreas com reincidência elevada de incêndios florestais.

Assim, importa perceber quais os padrões de UOS mais afetados pelos incêndios florestais, mas ao mesmo tempo, o período de retorno para a ocorrência destes eventos. O artigo que se apresenta na secção 4.2 (Meneses *et al.*, 2018a) aborda estas questões e apresenta as áreas com maior probabilidade de ocorrer novos incêndios florestais em Portugal continental.

Tabela 4.1. Área (ha) resultante do cruzamento entre a CLC 2018 e as áreas ardidas do ano 2017 (informação disponibilizada pelo ICNF) para Portugal continental.

Classe CLC (2018)	Área não afetadas por incêndios florestais	Área afetada por incêndios florestais (2017)	Área total da classe
Aeroportos	4739,8	36,1	4775,9
Agricultura com espaços naturais	703672,0	29267,9	732939,8
Áreas ardidas	5851,3	63814,9	69666,2
Áreas de deposição de resíduos	1227,3	41,1	1268,4
Áreas de extração mineira	14622,6	77,7	14700,4
Áreas em construção	2169,1	60,3	2229,5
Arrozais	44286,4	42,2	44328,6
Culturas anuais associadas às culturas permanentes	262993,0	7443,9	270436,8
Culturas anuais de regadio	258746,5	834,9	259581,4
Culturas anuais de sequeiro	669210,0	3860,7	673070,7
Equipamentos desportivos e de lazer	14430,2	27,9	14458,2
Espaços florestais degradados, cortes e novas plantações	1455704,8	159074,0	1614778,9
Espaços verdes urbanos	2905,9		2905,9
Estuários	16256,2		16256,2
Florestas de folhosas	760847,5	25888,2	786735,7
Florestas de resinosas	328003,6	68007,3	396011,0
Florestas mistas	418360,5	50569,2	468929,7
Indústria, comércio e equipamentos gerais	42673,1	507,2	43180,3
Lagunas litorais	7339,5	0,3	7339,8
Linhas de água	18082,6	243,7	18326,3
Mar e oceano	2239,2	1,0	2240,1
Matos	407612,6	61705,6	469318,2
Olivais	343794,7	4042,1	347836,8
Pastagens	227617,5	1133,8	228751,2
Pastagens naturais	39901,9	1271,1	41173,0
Pauis	1605,4	57,9	1663,3
Planos de água	66188,4	626,0	66814,4
Pomares	92905,0	657,0	93562,0
Praias, dunas e areais	9599,0	15,1	9614,0
Redes viárias e ferroviárias e espaços associados	11873,9	393,8	12267,7
Rocha nua	1195,9	212,2	1408,1
Salinas	6745,6		6745,6
Sapais	17425,0	49,4	17474,3
Sistemas agroflorestais	770271,5	1542,3	771813,8
Sistemas culturais e parcelares complexos	619463,8	14840,4	634304,2
Tecido urbano contínuo	36379,0	0,9	36379,9
Tecido urbano descontínuo	205947,2	1145,9	207093,1
Vegetação esclerofítica	237121,9	6416,3	243538,1
Vegetação esparsa	43137,5	3614,1	46751,7
Vinhas	209865,4	1195,3	211060,7
Zonas intertidais	3722,0		3722,0
Zonas portuárias	1686,8		1686,8
Total	**8388421,5**	**508717,5**	**8897139,0**

Os resultados apresentados no artigo deste capítulo são importantes para o ordenamento do território, destacando-se o mapa principal apresentado em anexo a este artigo (Figura 4.2), pois já se verificou que ocorreram muitos incêndios nas áreas demarcadas com probabilidade de ocorrência destes eventos (nos diferentes níveis de probabilidade). Destaca-se, a título exemplificativo, a ocorrência do incêndio florestal no início de agosto de 2018 na Serra de Monchique, em que a área ardida total deste incêndio (Figura 4.1) coincide em 89,3 % com a área demarcada pela probabilidade de ocorrência destes eventos (calculada com as áreas ardidas entre 1975 e 2017 – 1º semestre).

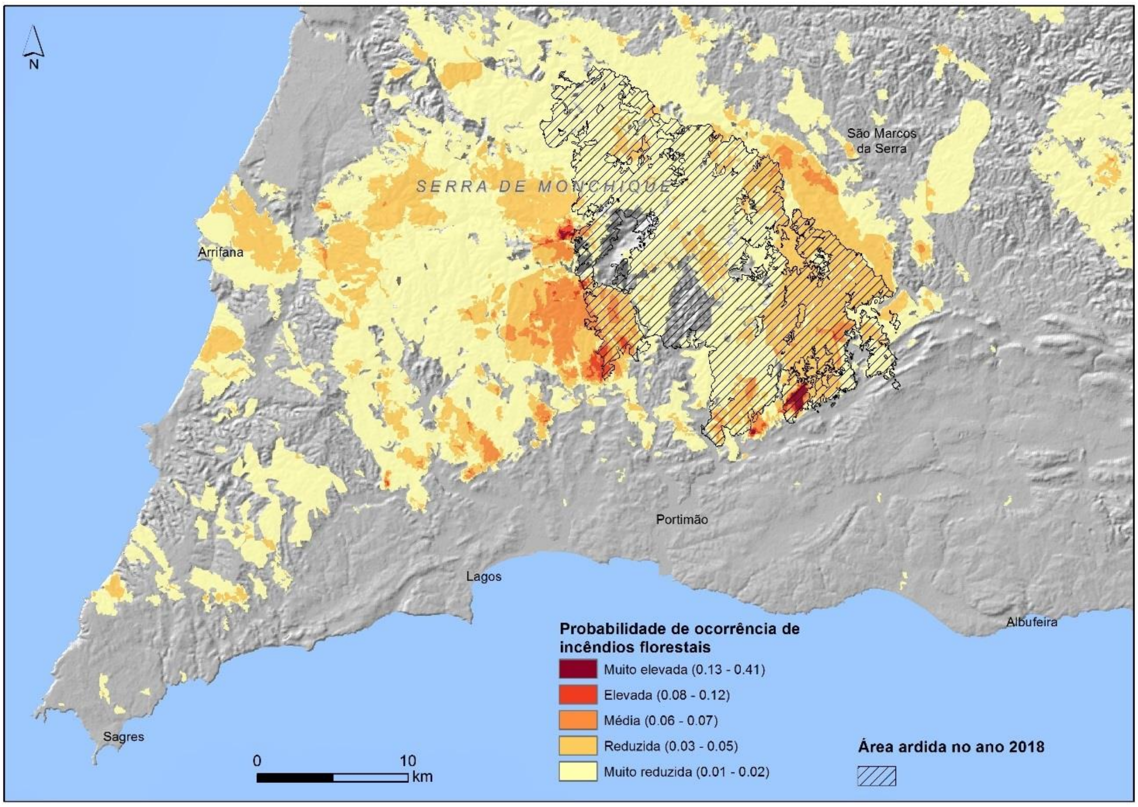

Figura 4.1. Probabilidade de ocorrência de incêndios florestais na Serra de Monchique, determinada com os registos de áreas ardidas entre 1975 e 2017 (primeiro semestre) (Meneses *et al.*, 2018a), e respetiva área ardida em agosto de 2018.

4.2. Artigo - Meneses, B.M.; Reis, E.; Vale, M.J.; Reis, R. (2018a) - Assessment of the recurrence interval of wildfires in mainland Portugal and the identification of affected LUC patterns. Journal of Maps, 14 (2), pp. 282-292.

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Assessment of the recurrence interval of wildfires in mainland Portugal and the identification of affected LUC patterns

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ABSTRACT

Wildfires are responsible for major land use and land cover (LUC) changes. These events are frequent and catastrophic in Portugal and are responsible for great damage and loss of human life. In this study, a map to assess the probability of wildfire occurrence (PWO) in mainland Portugal was created for the period 1975-2017 (first half of 2017). The PWO was obtained by the superimposition of all layers by adding all the burned areas for the total period. It was observed that the occurrences and extent of the burned areas are highly variable from year to year. The PWO map was cross-referenced with LUC geoinformation to evaluate the LUC types that were more affected by the wildfires. The results presented and the PWO maps are important for the management and planning of forest areas and for the creation of guidelines to implement preventive and reactive actions in case of wildfires.

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Wildfires; occurrence probability; return interval; LUC patterns; mainland Portugal

1. Introduction

The Mediterranean region has a long history of fires, and these events have been an important factor in forestry, agriculture, and grazing (Ferreira-Leite, Bento-Gonçalves, Vieira, Nunes, & Lourenço, 2016). However, the wildfires have devastated the Portuguese forest and small villages, with large consequences at different levels: social, economic, and environmental (Pereira, Pereira, Rego, Silva, & Silva, 2006).

The land use and land cover (LUC) of Portugal suffered large changes in recent years (Meneses, Reis, Pereira, Vale, & Reis, 2017; Pôças, Cunha, & Pereira, 2011; Santos, Tenedório, Rocha, & Encarnação, 2005), and these changes are explained largely by the occurrence of wildfires (Maia, Pausas, Vasques, & Keizer, 2012; Oliveira, Pereira, & Carreiras, 2012). The climate of Portugal promotes the occurrence of wildfires, as it has a rainy season during the spring, which is favorable to the development of vegetation, followed by a very warm period that triggers the development of large wildfires (Gomes, 2006) (on the coastline of Portugal, from north to south, the average temperature varies between 20.5°C and 23.6°C, the northwest of this country and a part of center sector varies between 19°C and 21°C, and areas to the south vary between 22°C and 24°C). The different types of climate create the conditions for the existence of different fire regimes in this territory (Parente, Pereira, & Tonini, 2016).

Several causes have been identified for the occurrence and development of large wildfires in Portugal: one is the increase in area covered by eucalyptus trees (Maia et al., 2012; Oliveira et al., 2012), and others are the increase in abandoned farmlands (Ferreira-Leite et al., 2016) and the reduction in pasturing (increasing the availability of fuel materials and the presence of shrubland, grass, etc.). The human ignitions of wildfires were also noted by Portuguese authorities as the cause for large occurrences. Some were caused intentionally and others were due to carelessness in the use of fire for the preparation of agricultural fields. Parente, Pereira, Amraoui, & Tedim (2018) indicate that a high percentage of wildfires in Portugal have a human origin, whether caused by accident, negligence, or arson.

Several studies on wildfires have been conducted in this country following different approaches and goals: the causes (Pereira et al., 2006), severity and regeneration of vegetation (Maia et al., 2012), incidence (Bergonse & Bidarra, 2010; Ferreira-Leite et al., 2016; Oliveira et al., 2012), and environmental impacts (Bento-Gonçalves, Vieira, Úbeda, & Martin, 2012; Esteves et al., 2012; Meneses, 2013; Meneses & Cortez, 2015; Miranda et al., 2010; Teodoro & Duarte, 2013), among others.

The recurrence of large fires was assessed by Ferreira-Leite, Bento-Gonçalves, and Vieira (2011) for the period 1981–2010, and the results were crossed with some explanatory variables (physical and human

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features). The assessment and validation of wildfire susceptibility and hazard in Portugal were also performed by some authors. For example, Verde and Zêzere (2010) used 30 years of wildfires records (1975–1994), resulting in a wildfire hazard map.

However, an in-depth assessment on wildfires in Portugal is needed, i.e. based on the knowledge of the locations where fires occur, to determine the types of LUC most affected (incidence), assess the recurrence in these locations and check whether this is consistent in consecutive periods.

The main goal of this research was to map the probability of wildfire occurrence (PWO) in mainland Portugal and the assessment of the spatial and temporal distribution of wildfires (burned areas and occurrences). The second goal was the determination of PWO by different types of LUC and to identify the LUC patterns showing greater fire incidence. The return period distribution of these events (burned areas and occurrences) was also evaluated.

2. Materials and methods

2.1. Study area

The study area is mainland Portugal (88,962.5 km^2). This territory is subdivided into five NUTS II (Nomenclature of Territorial Units for Statistics): north (23.8% of the area), centre (31.6%), Lisbon (3.6%), Alentejo (35.4%), and Algarve (5.6%).

The relief of this territory is quite irregular and is characterized by deeply incised valleys surrounded by mountains in the north and by lower, less rugged relief in the south (Figure 1(A)).

The climate is strongly influenced by the Atlantic Ocean and the Mediterranean Sea due to the transition between the Mediterranean and the Atlantic climatic conditions. The rainfall regime is characterized by high spatial and inter-seasonal variability. The mean annual precipitation (MAP) ranges from less than 500 mm in the south and northeast to more than 2000 mm in the northwest. The MAP tends to increase with increasing latitude, elevation, and proximity to the Atlantic Ocean. Summer months (June, July, and August) are particularly dry, and the rainfall is concentrated mainly in the period lasting from October to March (climatological normals from Portuguese Institute for Sea and Atmosphere, IPMA).

The LUC has a greatly contrasting spatial distribution (Figure 1(B)): forests and shrubland predominate in the centre and north, with high occurrence of eucalyptus and resinous plants (mainly *Pinus pinaster*); the largest agricultural areas are found in the south, essentially in the Alentejo region, and are characterized

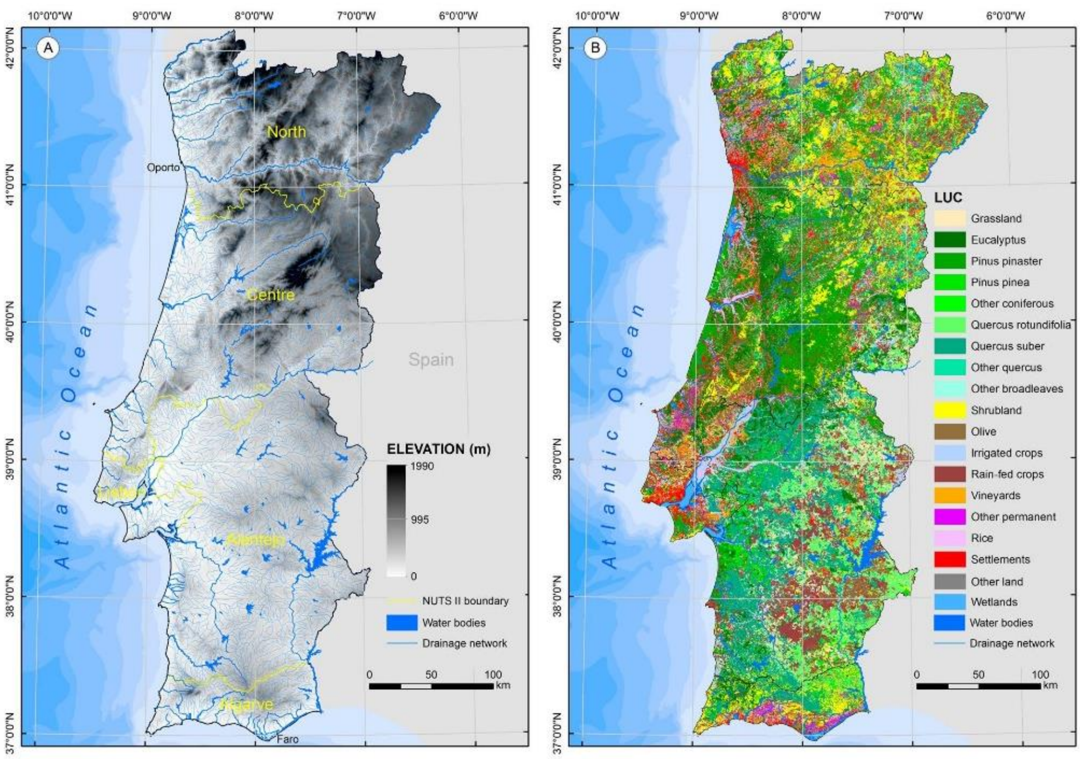

Figure 1. Mainland Portugal: (A) – elevation (data of Digital Elevation Model from the GMES RDA project, made available by the European Environment Agency); (B) –land use and land cover (LUC), 2010 (official land cover map of Portugal, provided by the General Directorate for Territorial Development, DGT).

by important extents of *Quercus* areas; and settlements predominate in the littoral areas, where the more important metropolitan areas (Lisbon and Oporto) are located.

2.2. Data

The geoinformation (GI) on burned areas (vector format, shapefile) for the study area was produced by the Institute of Agronomy (ISA-UL) (1975–1989), the Institute for the Conservation of Nature and Forest – ICNF (Portugal) (1990–2016) and the European Forest Fire Information System (EFFIS) (first half of 2017). The time series used in the wildfires map production (1975–2016 and first semester of 2017) is the compilation of all data available by the institutions mentioned above. The ICNF data were created from EFFIS data (obtained by remote sensing) and the visual interpretation of orthophotos. The previous process was also used by ISA-UL, which completed analyses of Landsat MSS (1975–1983) and TM/ETM+ (1984–2009) satellite images. The minimum mapping unit for these data is 1 ha. Each polygon that delimits a burned area represents an occurrence, independently of the causes of the ignition (propagation, human or natural ignition, etc.). Therefore, the total occurrences in each year are represented by the number of polygons represented in this year independent of whether a wildfire was caused or influenced by other wildfires that occurred in the region.

The LUC GI (Carta de Ocupação do Solo - COS in Portuguese; or Portuguese Land Cover Map in English) is available in the General Directorate for Territorial Development (DGT) website for the years 1995, 2007, and 2010 and has the following characteristics: scale 1/25,000; minimum mapping unit of 1 ha; vector data model (polygons); and a 20-m minimum distance between lines. The cartographic information of 2007 was obtained from the photointerpretation of orthophotos (resolution of 0.5×0.5 m), a process aided by IRS (Indian remote sensing) and AWiFS (advanced wide field scanner) satellite imagery and geographic information of cadastral surveys (agriculture and forestry) performed at DGT. All results were validated (geometrically and thematically) by the DGT to obtain data with high accuracy and quality (IGP, 2010). To produce the LUC cartography of 2010, DGT used the same methodology used for the cartography of 2007. The LUC cartography of 1995, also produced by DGT, was obtained using the vectorial data of LUC boundaries of 2007 that were updated to the 1995 LUC based on orthophotos and satellite images of this year (1995). The LUC cartography for the year 1995 is only available with the nomenclature used in the Kyoto report (DGT, 2014). For this reason, and to allow LUC comparison between different periods, the legend of the LUC maps of 2007 and 2010 follows the nomenclature used in the Kyoto report.

The production of the various maps also used complementary GI from the Portuguese Environmental Agency (elevation, drainage network and water bodies) and from the Portuguese Hydrographic Institute (bathymetry and digital terrain model of West of Iberian Peninsula Oceanic region – hydrographic zero).

2.3. Methodology

Commercial GIS software was used to perform the spatial analysis of wildfire distributions and to determine the recurrence of these events (burned area). Later, all the GI integrated in the PWO model was converted to raster (25×25 m).

In the production of the PWO map (Main Map), each annual event (individual layers) was assigned the value '1' (burned area) in the reclassification of the GI. The PWO was obtained by the superposition of all layers by adding all the burned areas for the total period (Equation (1)). A lower PWO indicates that an area is affected by at least 1 wildfire in the time series (T) of burned areas and increases to the highest PWO (areas most affected by wildfires).

$$\mathrm{PWO} = \frac{\sum_{i=1}^{n} Ba}{T} \tag{1}$$

where *PWO* represents the probability of wildfire occurrence, *Ba* the occurrences with burned area in each year and *T* the total period (years).

PWO was represented in quintiles in order to allow the user to easily understand the visible PWO, i.e. which regions are most affected by wildfires (the places with greater PWO). The colors used in the legend for the probability vary between light yellow (1) and red (5), highlighting the places where great care should be taken (preventive and reactive intervention) concerning the occurrence of wildfires.

The PWO was crossed with LUC GI (Figure 2) to identify the affected LUC patterns. This process was complemented by crossing the LUC available (1995, 2007, and 2010) by different periods of burned areas (total number of occurrences): 1995–2006 wildfire occurrences (WO) and LUC 1995; 2007–2009 WO and LUC 2007; 2010–2017 WO and LUC 2010. These procedures are important to identifying the LUC patterns that are more affected by the wildfires.

The Weibull probability distribution function was applied to calculate the return period for the forest fire occurrences (1975–2017, the first half of 2017, in mainland Portugal) and total burned area.

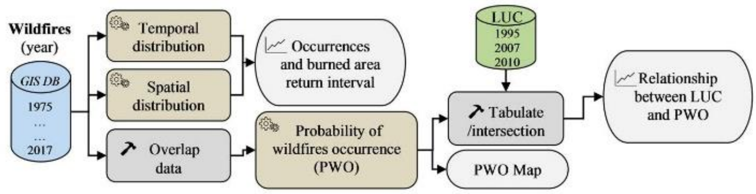

Figure 2. Methodological scheme.

3. Results analysis

3.1. Wildfires in mainland Portugal

The occurrence of wildfires in mainland Portugal varied considerably in the period 1975–2017 (first half of 2017). However, in the past few years (especially 2010–2013) (Figure 3) there was an increase in the number of fires. In general, an increase in the number of occurrences was observed, but the total burned area per year does not follow this trend. In fact, the series for the years of 2003 and 2005 shows the largest burned area (440386 and 336594 ha, respectively).

The wildfires occurred mainly in the centre and north regions of Portugal (Figure 4), where the main forest areas (pinewoods, eucalyptus, and *Quercus*) are present. However, the extent of burned areas is increasing in the past decades, in the center of Portugal, for example, the wildfires that occurred at 17 and 18 June 2017 (more than 40000 ha), which resulted in 64 dead people according to the Portuguese National Civil Protection Authority.

In the Main Map the value range goes from 0.01 to 0.41; the values were classified using quintiles, resulting in the next classes: very high (0.13–0.41), high (0.08–0.12), medium (0.06–0.07), low (0.03–0.05), and very low (0.01–0.02).

The incidence of wildfires in this territory is very high, with areas that burned 17 times in the past 41.5 years that correspond to the areas with high PWO (Main Map). The middle sector of the centre region stands out by the extent of burned areas and the high values of PWO. These areas are especially in the Zêzere watershed, where the important surface freshwater reservoirs of Cabril and Castelo de Bode dams are located. The forest of this watershed is predominantly resinous; hence the easy spread of wildfires and the difficulty of extinguishing these fires (also because of the rough relief), resulting in large extents of burned area. Currently, the forest of this watershed is composed mainly by scrub and/or herbaceous vegetation associations, pastures, and other tree species (Meneses, Reis, Vale, & Reis, 2016), being the result of not only the burned areas' extent but also of the incidence of these events and not allowing forest regeneration, particularly of coniferous species.

The location of burned areas was influenced by the location of certain types of forests. The north and centre regions present a greater tendency for the

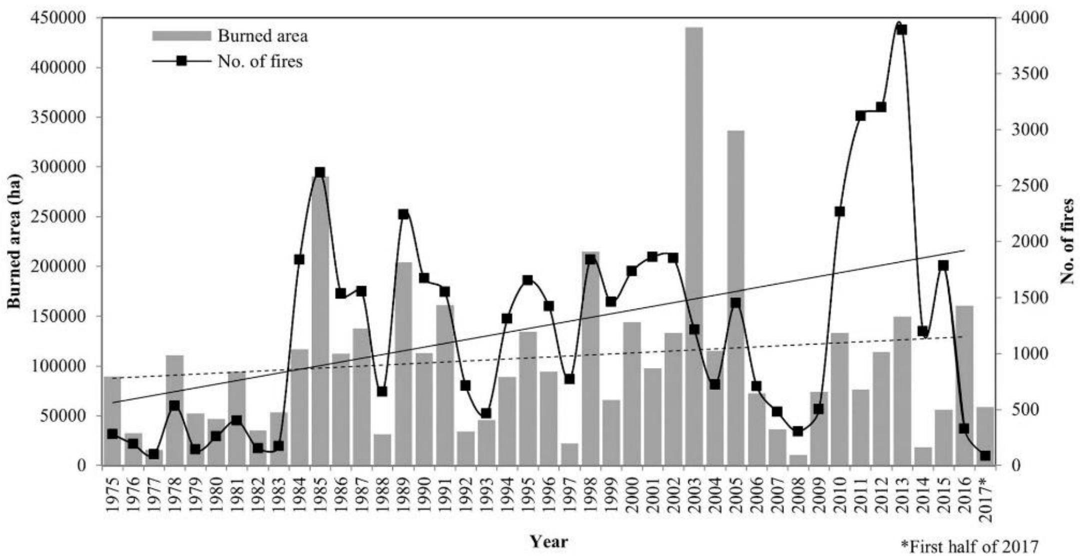

Figure 3. Burned area and number of wildfires (1975–2017) in mainland Portugal (straight lines represent the linear trend for burned area (dashed) and for No. of fires (solid) 1975–2016).

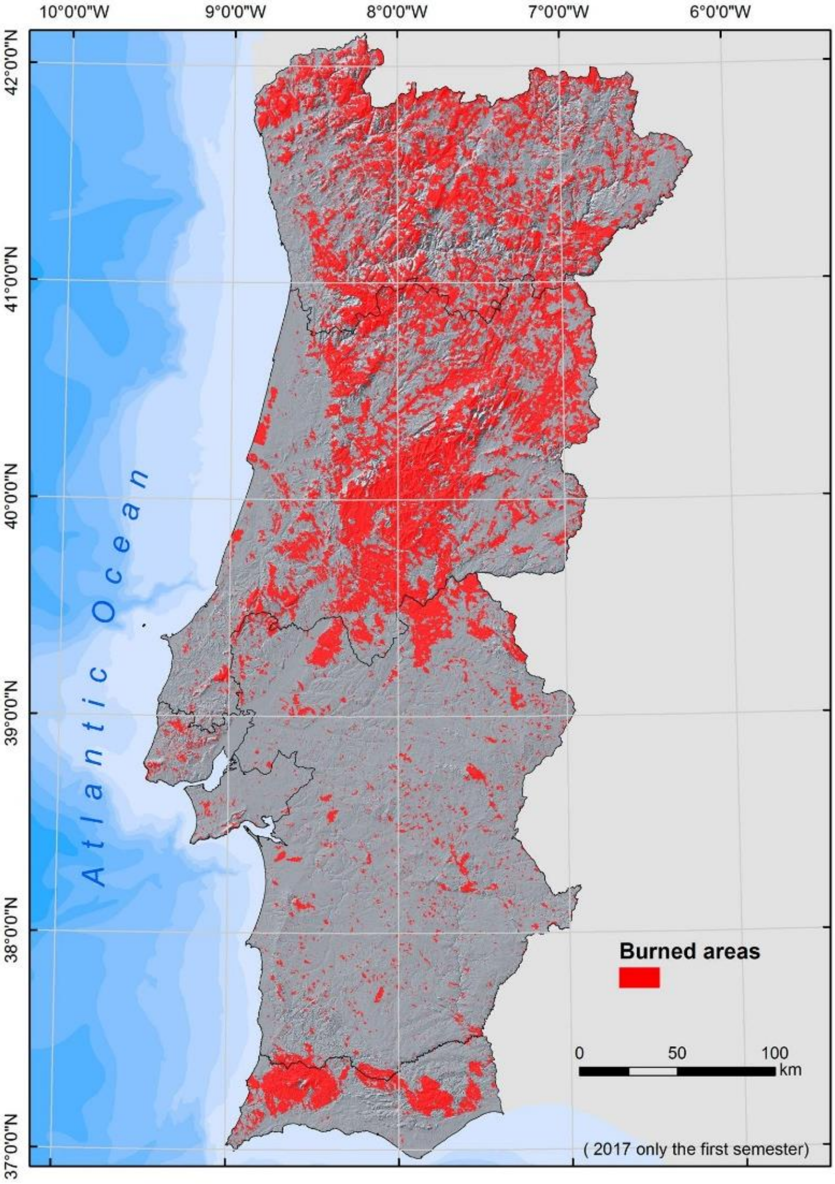

Figure 4. Burned areas in mainland Portugal resulting from wildfires from 1975 to 2017 (data of ICNF, EFFIS and ISA).

occurrence of several fires mainly due to the presence of large forest patches (pinewoods and eucalyptus). However, the north region exhibits the greatest total area burned by a factor of at least 17 (Table 1). We should also note that these two regions (north and centre) present values very close to those observed in general (Portugal) for the burned areas registered in different times (occurrences) (Table 1).

Approximately 27% of the area of mainland Portugal was affected by wildfires from 1975 to the first half of 2017, including 14.6% of this territory that burned only one time, i.e. 54.5% of the total burned area (Table 2). The percentage of burned area reduces with the number of occurrences, and this percentage reduces greatly if an area is affected by fire more than five times (<1% of total area).

The burned area is also very variable when the regions are compared. The north and centre present more occurrences compared to other regions, and the burned area is very high for the first occurrences (i.e. in first years). The Algarve region presents a distinct case with few occurrences of fire in the same area, but the total burned area is high as a result of the large size of each occurrence.

The return intervals of the wildfire occurrences (Ori) and burned area (Bri) are different, especially between the first year in which occurred wildfires to the next years, with a highlight on the natural break

Table 1. Burned areas (%) in mainland Portugal and NUTS II, according to the number of times that the areas burned (1975–2017, first half of 2017).

		NUTS II (total area by each NUTS)				
	Portugal	North	Centre	Lisbon	Alentejo	Algarve
Total area burned at least one time	100	100	100	100	100	100
Area burned one time	65.74	70.26	65.66	55.71	52.68	55.75
Total area burned at least two times	47.05	57.99	48.14	20.24	10.18	21.37
Area burned two times	31.47	40.52	31.31	11.42	5.36	11.49
Total area burned at least three times	23.64	33.40	22.22	4.68	1.02	3.00
Area burned three times	15.89	23.07	14.49	2.60	0.535	1.62
Total area burned at least four times	12.085	18.67	10.21	0.926	0.085	0.422
Area burned four times	8.14	12.74	6.75	0.526	0.045	0.238
Total area burned at least five times	6.24	10.07	4.91	0.225	0.010	0.104
Area burned five times	4.20	6.81	3.29	0.126	0.0047	0.054
Total area burned at least six times	3.23	5.28	2.49	0.054	0	0.0052
Area burned six times	2.17	3.55	1.67	0.027	0	0.0026
Total area burned at least seven times	1.67	2.73	1.28	0	0	0.0001
Area burned seven times	1.11	1.82	0.851	0	0	0
Total area burned at least eight times	0.841	1.38	0.645	0	0	0
Area burned eight times	0.552	0.911	0.420	0	0	0
Total area burned at least nine times	0.406	0.672	0.307	0	0	0
Area burned nine times	0.263	0.440	0.195	0	0	0
Total area burned at least ten times	0.188	0.319	0.136	0	0	0
Area burned ten times	0.120	0.208	0.083	0	0	0
Total area burned at least eleven times	0.083	0.151	0.051	0	0	0
Area burned eleven times	0.052	0.097	0.030	0	0	0
Total area burned at least twelve times	0.033	0.065	0.016	0	0	0
Area burned twelve times	0.021	0.043	0.0087	0	0	0
Total area burned at least thirteen times	0.014	0.031	0.0036	0	0	0
Area burned thirteen times	0.0089	0.020	0.0020	0	0	0
Total area burned at least fourteen times	0.0065	0.020	0.0008	0	0	0
Area burned fourteen times	0.0039	0.0094	0.0004	0	0	0
Total area burned at least fifteen times	0.0023	0.0056	0.0001	0	0	0
Area burned fifteen times	0.0013	0.0034	0	0	0	0
Total area burned at least sixteen times	0.0007	0.0019	0	0	0	0
Area burned sixteen times	0.0004	0.0011	0	0	0	0
Total area burned at least seventeen times	0.0003	0.0007	0	0	0	0
Area burned seventeen times	0.0001	0.0003	0	0	0	0

of Ori (Figure 5). The probability that the determined number of occurrences is exceeded is very high for short return periods (Figure 5, graph in the right). For example, at the end of the first year, there is an approximately 50% probability of exceeding the expected number of occurrences and burned area (86 occurrences and 10573 ha, respectively). However, increases in Ori are different compared to the increase in Bri after the first years, and there is a higher Ori, resulting in large return periods.

The occurrence of extreme fires, especially considering the extent of burned area, has higher return periods, which could be favorable for the regeneration of natural vegetation in these areas. On the other hand, the higher the productivity of plants (biomass) and the greater accumulation of forest fuel facilitate an increase of fire consequences depending on the severity and intensity of these events (Fernandes & Rego, 2010).

4. Discussions

4.1. Framework of wildfires

Wildfires are recurrent events in mainland Portugal. This fact is mentioned by several authors (Ferreira-Leite et al., 2011; Ferreira-Leite et al., 2016; Oliveira et al., 2012; Verde & Zêzere, 2010) and confirmed in this research. For annual data, the number of occurrences does not have strong correlation with the burned area. In the most recent years, more wildfires occur each year, but the total burned area is reduced. However, large wildfires have occurred, for example, the fires in 2003 that resulted in large burned areas (Montiel-Molina, 2013), and these areas are the most significant in the center of Portugal, principally in the Zêzere watershed, and have serious environment implications (Meneses, Reis, Vale, & Saraiva, 2015). The wildfires are not distributed uniformly throughout the study area. This fact was also observed by Nunes, Lourenço, & Meira (2016) both in terms of ignition density and burned area.

The incidence of wildfires may be a factor that explains the perturbation of water quality parameters (WQP), mainly for certain physicochemical elements and compounds derived from wildfires in shallow water, providing the increase in the levels of specific WQP, a fact verified by Meneses, Reis, Vale, and Saraiva (2015). The subsequent burning of the forest material in short periods does not allow for normal forest regeneration, especially for coniferous forest (Pérez-Cabello & Ibarra Benlloch, 2003). However, the occurrence of the next wildfires in the same area, due to lower available biomass, results in a smaller concentration of the elements and compounds deposited in the surface of soils (e.g. ash content post-fire), and this factor can explain the reduction in the levels of determined WQP

Table 2. Relation of the burned areas (%) in mainland Portugal and NUTS II according to the number of occurrences and total burned area (1975–2017).

	Portugal		NUTS II									
			North		Centre		Lisbon		Alentejo		Algarve	
	Burned area/ Total area	Burned area/ Total burned area	Burned area/ Total area	Burned area/ Total burned area	Burned area/ Total area	Burned area/ Total burned area	Burned area/ Total area	Burned area/ Total burned area	Burned area/ Total area	Burned area/ Total burned area	Burned area/ Total area	Burned area/ Total burned area
Area burned one time	14.62	54.53	15.85	41.29	19.83	51.01	6.40	80.09	8.65	89.80	22.48	77.68
Area burned two times	6.13	22.86	9.20	23.97	10.29	26.47	1.22	15.22	0.88	9.16	5.56	19.20
Area burned three times	2.98	11.11	5.68	14.79	4.84	12.45	0.30	3.79	0.09	0.95	0.78	2.70
Area burned four times	1.49	5.57	3.44	8.97	2.08	5.35	0.05	0.68	0.01	0.07	0.09	0.30
Area burned five times	0.76	2.85	1.98	5.16	0.90	2.33	0.01	0.16	0.001	0.01	0.03	0.11
Area burned six times	0.39	1.46	1.05	2.74	0.44	1.13	0.005	0.06	0	0	0.002	0.006
Area burned seven times	0.21	0.78	0.57	1.48	0.23	0.60	0	0	0	0	0	0
Area burned eight times	0.11	0.43	0.31	0.80	0.13	0.33	0	0	0	0	0	0
Area burned nine times	0.06	0.22	0.16	0.41	0.07	0.17	0	0	0	0	0	0
Area burned ten times	0.03	0.11	0.07	0.19	0.04	0.09	0	0	0	0	0	0
Area burned eleven times	0.02	0.06	0.04	0.11	0.02	0.04	0	0	0	0	0	0
Area burned twelve times	0.01	0.02	0.01	0.04	0.01	0.02	0	0	0	0	0	0
Area burned thirteen times	0.002	0.01	0.01	0.02	0.001	0.003	0	0	0	0	0	0
Area burned fourteen times	0.001	0.005	0.005	0.01	0	0.001	0	0	0	0	0	0
Area burned fifteen times	0.0005	0.002	0.002	0.01	0	0	0	0	0	0	0	0
Area burned sixteen times	0.0001	0.001	0.001	0.002	0	0	0	0	0	0	0	0
Area burned seventeen times	0.0001	0	0	0.001	0	0	0	0	0	0	0	0
Total burned area	26.81	100	38.38	100	38.88	100	7.99	100	9.63	100	28.94	100
Area not burned	73.19		61.62		61.12		92.01		90.37		71.06	

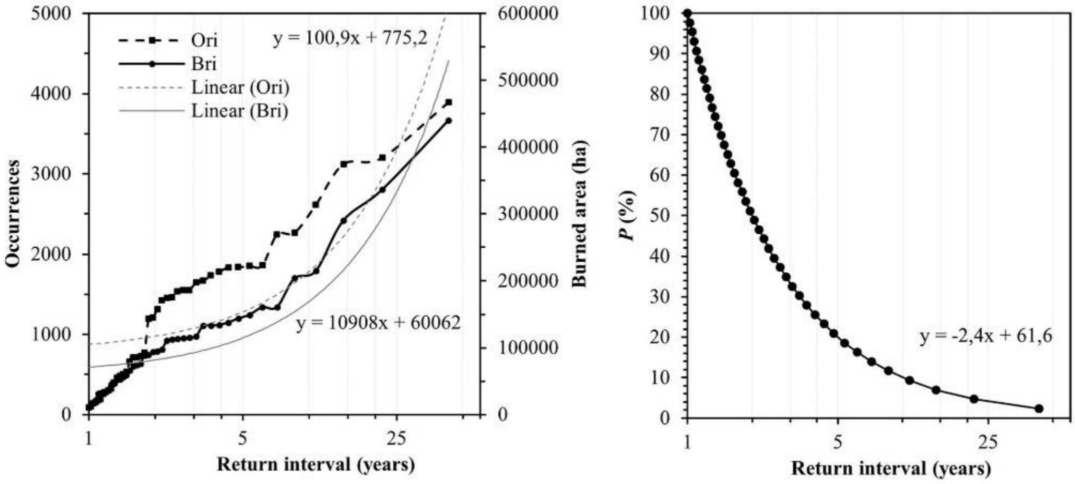

Figure 5. Wildfire occurrences (Ori) and burned area (Bri) return interval (left) and the probability (*P*) of the determined number occurrences and burned area to be exceeded (right), in mainland Portugal.

in the main superficial freshwater reservoirs (Meneses et al., 2015; Shin, Sidharthan, & Shin Young, 2002; Vila-Escalé, Vegas-Vilarrúbia, & Prat, 2007).

Other negative consequences were the impacts of wildfires on human life (Finlay, Moffat, Gazzard, Baker, & Murray, 2012; Fowler, 2003), and Portugal stands out in the international context for the number of deaths year after year. The year 2017 stands out in this report, with 64 deaths in a fire in the centre region. The loss of forest also influences the biotic diversity, induces ecological perturbations, reduces employment (directly or indirectly linked to the forest), and causes socio-economic difficulties for the affected populations, among other consequences. The maps of burned areas and PWO are important to evaluate these consequences and for the creation of preventive and reactive measures.

4.2. Relation between LUC and wildfires

Wildfires occur most frequently in shrubland areas, eucalyptus, and *Pinus pinaster* forests (Table 3), but the incidence of wildfires in the areas with these LUC types is very variable between different periods. However, the PWO is very high in shrubland areas compared to other LUC types, and this result agrees with the high frequency of burned area presented in Table 3. The results obtained reflect also the fast regeneration of this type of vegetation in the burned areas and the creation of new conditions that facilitate the next wildfires due to the biomass availability.

The eucalyptus forest is noted by several authors as being very prone to large wildfires (Catry, Moreira, Tujeira, & Silva, 2013; Ferreira-Leite et al., 2016; Oliveira et al., 2012) due to the characteristics of this vegetation (pyrophytes species) and the rapid regeneration of this species (areas more favorable to the occurrence of more fires). However, the PWO of this forest type is lower compared to that of *Pinus pinaster*. On the one hand, the decrease in pine forest area in Portugal is linked to wildfires (slow regeneration after the first wildfire, but if it was affected by other wildfires in a short period, the regeneration of this species does not occur because young pines do not have seeds for the regeneration process), and this trend could the result of fire severity or increasing fire recurrence (Lucas-Borja et al., 2016). On the other hand, the high incidence of the pinewood nematode vector in Portugal was also responsible for heavy losses of pine trees (Autoridade Florestal Nacional, 2012; Meneses et al., 2017). The incidence of this vector constitutes a large disincentive to replanting new pine forests, and after the wildfires, most landowners opt for other alternatives. This fact also explains the reduction of this type of forest in the study area.

Arnan, Quevedo, and Rodrigo (2013) indicate that changes in fire regimes can give rise to new types of forest cover or increase the distribution range of scarce forests in a regional context. This phenomenon is indirectly evidenced in this research, and we highlight the fact that the burned areas with a high incidence of wildfires have even more difficulty in regenerating forests, especially pine forests, when those affected by fires are later occupied essentially by shrubland. This LUC (in the Portuguese territory) was quantified in recent research presented by Meneses, Reis, Vale, and Reis (2018). This fact explains the extensive burned area and high PWO observed in this LUC type at different times.

In general, the *Quercus* forest exhibits reduced burned area compared to shrubland, *Pinus pinaster*, and eucalyptus forest, and the PWO is also lower in this type of LUC (Figure 6). This type of vegetation is more resistant to fire (Curt, Bertrand, Borgniet,

Table 3. LUC and the number of wildfire occurrences (% burned area) in mainland Portugal.

	LUC 1995							LUC 2007			LUC 2010				
LUC Type	**1st occur.**	**2nd occur.**	**3rd occur.**	**4th occur.**	**5th occur.**	**6th occur.**	**7th occur.**	**1st occur.**	**2nd occur.**	**3rd occur.**	**1st occur.**	**2nd occur.**	**3rd occur.**	**4th occur.**	**5th occur.**
Grassland	2.93	0.46	0.13	0.04	0.00	0	0	3.97	0.09	0	2.06	0.18	0.01	0.001	0
Shrubland	22.95	7.26	1.92	0.55	0.09	0.008	0.001	41.20	1.11	0.001	28.34	5.47	0.83	0.03	0.001
Eucalyptus globulus	11.99	1.92	0.25	0.04	0.01	0	0	6.31	0.03	0	17.01	1.27	0.14	0	0
Pinus pinaster	20.54	2.90	0.38	0.07	0.01	0.001	0	15.22	0.27	0	19.25	1.74	0.13	0.001	0
Pinus pinea	0.49	0.02	0.00	0	0	0	0	0.47	0.003	0	0.66	0.02	0.001	0	0
Other coniferous	0.06	0.01	0.00	0.001	0.001	0	0	0.25	0.001	0	0.17	0.02	0.003	0	0
Quercus rotundifolia	1.58	0.09	0.02	0.001	0	0	0	2.51	0.05	0	0.74	0.06	0.001	0	0
Quercus suber	5.96	0.32	0.02	0.003	0.002	0	0	1.58	0.02	0	3.24	0.05	0.002	0	0
Other *Quercus*	2.43	0.60	0.12	0.02	0.003	0	0	6.78	0.10	0	4.11	0.37	0.03	0.001	0
Irrigated crops	0.51	0.04	0.01	0.001	0	0	0	1.12	0.001	0	0.91	0.04	0.00	0	0
Olive	1.82	0.09	0.01	0	0	0	0	1.01	0.001	0	1.28	0.03	0.001	0	0
Other broadleaves	1.84	0.30	0.05	0.01575	0.00342	0	0	6.56	0.43	0	3.60	0.25	0.02	0	0
Rain-fed crops	4.23	0.37	0.05	0.00627	0	0	0	5.37	0.04	0	3.76	0.19	0.01	0	0
Rice	0.02	0	0	0	0	0	0	0.04	0	0	0	0	0	0	0
Vineyards	0.28	0.01739	0.002	0	0	0	0	0.29	0.001	0	0.45	0.02	0	0	0
Other land	2.14	0.88	0.29	0.09	0.02	0.002	0	4.00	0.14	0	1.95	0.28	0.03206	0.001	0
Other permanent	0.19	0.00861	0.001	0	0	0	0	0.23	0.001	0	0.18	0.00	0	0	0
Settlements	0.32	0.01814	0.002	0	0	0	0	0.45	0.02	0	0.74	0.03	0	0	0
Wetlands	0.19	0.00596	0	0	0	0	0	0.32	0.000	0	0.26	0.00	0	0	0

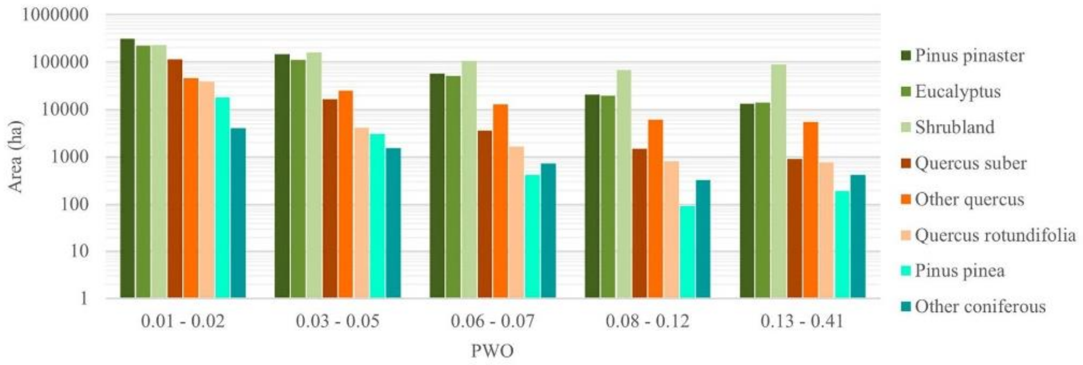

Figure 6. Distribution of forest classes area (COS 2010) in mainland Portugal by the classes of PWO (represented in quintiles).

Ferrieux, & Marini, 2010), and this factor can explain the low burned area observed in *Quercus rotundifolia*, *Quercus suber* and other *Quercus* areas (Table 3) compared to the types of forest mentioned before. Evidently, these LUC types exhibit lower PWO, explained by a low incidence of fires in this type of forest.

Some agricultural areas also exhibit burned areas, which can be caused by the propagation of wildfires or by locals starting fires (due to uncontrolled burnings) and consequent propagation to the forest, but the fire incidence in these areas is low (anthropic management activities) (Table 3).

5. Conclusions

Portugal has a history of catastrophic wildfires. Those more affected are the centre and north regions, but these regions also presented the highest percentage of forested area. The incidence of wildfires is most significant in the centre (Main Map), where the largest wildfires also occurred in the past years.

The return period of wildfires with the reduced burned area is very low in mainland Portugal; however, there is a high probability of many occurrences of small-magnitude fires in relatively short periods.

Pinus pinaster and *Eucalyptus globulus* presented high PWO, but shrubland stands out for the highest area burned and highest PWO. This fact is explained by the regeneration of this vegetation type in burned areas and its predominance in the Portuguese territory.

The PWO map (Main Map) is important in identifying the places most affected by these events and identifying where the next wildfires can occur based on the probability calculated from the incidents recorded in the past. This map also provides support for the creation of broad guidelines for economic and territorial policies, especially for the planning and management of forests and other natural resources. This map also allows for new approaches to fire probability studies in mainland Portugal and will allow for the validation of future fire risk maps produced by different institutions.

The data and procedures used in this paper possess two characteristics that may in some way influence the results and that should be taken into account in future research. First, the relatively long periods of the 1995–2006 and 2010–2017 series do not provide any assurance that the various land cover classes present in the reference cartography are maintained throughout these series. Since it is not possible to obtain other dates for land cover cartography at this stage, one possibility is to use a shorter period of burned area data after each land cover date in order to reduce this possible discrepancy. Second, in the areas burned in each year, there is a change in the land cover; so new wildfires will affect a different class compared to those present in the reference land cover cartography. One possible way to overcome this situation is to update each year with the burned areas mapped in the previous year so that each land cover class is replaced an 'area burned in the previous year' class.

Software

ESRI ArcGIS 10.5 was used to evaluate the wildfire distributions, model the PWO, and design the maps.

Disclosure statement

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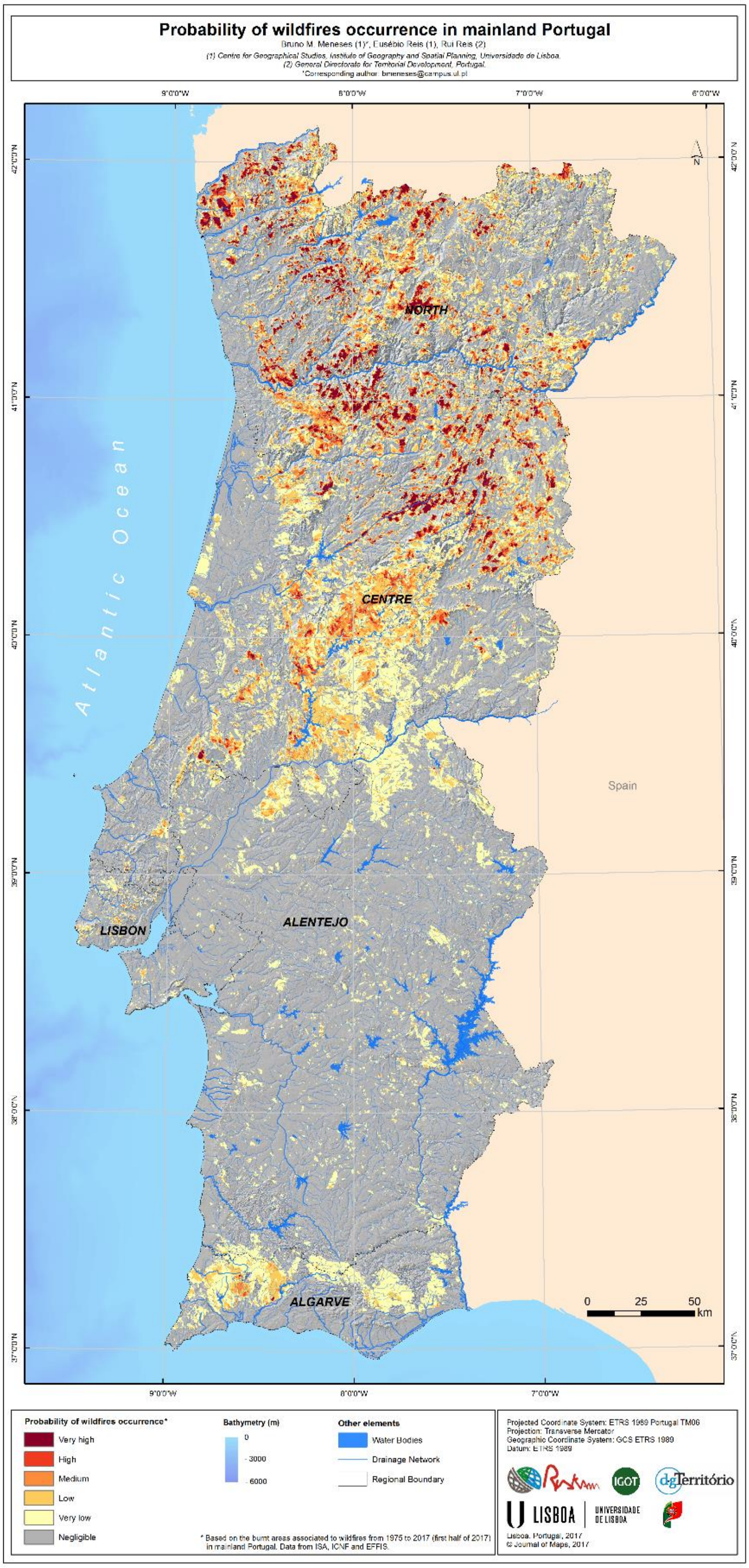

Figura 4.2. Mapa principal do artigo Meneses *et al.* (2018a).

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Capítulo 5

ALTERAÇÕES DE USO E OCUPAÇÃO DO SOLO E QUALIDADE DA ÁGUA

5.1. INTRODUÇÃO

São várias as implicações ambientais resultantes das AUOS, facto já evidenciado nos capítulos anteriores, mas é importante abordar algumas destas implicações com maior detalhe, nomeadamente as implicações na qualidade da água.

Nem sempre é fácil estabelecer uma ligação direta entre uma alteração de um determinado tipo de UOS com a variação de um determinado parâmetro físico-químico da água, nomeadamente na água de albufeiras com diversos cursos de água a contribuírem para a mesma, porque as fontes de poluição podem ser difusas e nem sempre existe informação suficiente para as detetar, por exemplo a aplicação de produtos fitofarmacêuticos em áreas agrícolas que indiretamente podem ser arrastados através da escorrência superficial para os corpos de água. Alguns elementos destes produtos podem chegar até albufeiras importantes, podendo aumentar a concentração de alguns parâmetros físico-químicos, ou podem simplesmente ser dissolvidos devido ao volume de água existente.

Contudo, é possível estabelecer relações entre a variação de área de determinados tipos de UOS com a variação pontual dos parâmetros de qualidade da água (PQA). Esta é a problemática abordada no artigo da secção 5.2 (Meneses *et al.*, 2015), onde foram analisadas as AUOS com os dados dos PQA em diferentes setores da bacia hidrográfica do rio Zêzere, delimitados estrategicamente em função da localização de albufeiras com estações de medição dos PQA (o material suplementar deste artigo encontra-se no anexo 4). Para este efeito, utilizou-se a geoinformação da CLC, nomeadamente a CLC 2000 e CLC 2006. O aumento de área agrícola, a perda de determinados tipos de floresta e o aumento de áreas ardidas resultantes dos incêndios florestais, têm correlação positiva com a variação dos PQA analisados na área de estudo, nomeadamente o aumento de nitratos e nitritos, em grande parte ligados à exploração agrícola, ou a variação do pH derivado da desflorestação. A artificialização dos solos, nomeadamente a expansão da área urbana e industrial, reflete-se sobretudo na correlação positiva com o aumento de coliformes fecais, o que evidencia a existência de uma rede de esgotos e respetivo tratamento deficitária, ou mesmo a descarga ilegal de resíduos sólidos domésticos ou industriais diretamente nos cursos de água. Este tipo de avaliação das AUOS revela-se importante, por um lado na remediação e criação de medidas reativas para reduzir ou eliminar a possível alteração da qualidade da água dos corpos de água, seja a eliminação na fonte da poluição (quando detetada), seja no tratamento da água a jusante (estações de tratamento); por outro lado, estes resultados podem ser utilizados na gestão do território, sobretudo na criação de medidas preventivas que visem reduzir ou eliminar a possível alteração da qualidade da água. Algumas destas medidas podem ser por exemplo a inibição da utilização de produtos químicos nas áreas agrícolas envolventes aos corpos de água que possam se lixiviados ou arrastados pela escorrência superficial, a restrição da urbanização em áreas específicas, o melhoramento da rede de esgotos e seu tratamento, entre outras medidas.

Conforme apresentado no artigo da secção 5.2, a expansão urbana tem efeitos na variação da qualidade da água. Neste sentido, evidencia-se a avaliação de impactes derivados da continuação do crescimento urbano na qualidade da água, pois poderá estar em causa o aumento da poluição de cursos de água que tornaram imprópria a água, seja para consumo humano, seja para outros fins. Com base nesta premissa, analisaram-se as AUOS na bacia hidrográfica do rio Zêzere, mas neste caso foram utilizadas as CLC de 1990, 2000 e 2006, a partir do qual se determinou o crescimento urbano, resultados posteriormente cruzados com os PQA da principal albufeira desta bacia hidrográfica, i.e., Castelo de Bode (armazena a água que abastece a região de Lisboa, daí ser considerada uma albufeira estratégica). A partir das relações encontradas entre a variação dos PQA com as AUOS nos diversos momentos considerados, calculou-se a tendência de variação futura dos PQA, mas neste caso integraram-se também os resultados da probabilidade de artificialização do solo apresentados no artigo da secção 3.4. Todos os procedimentos, resultados obtidos e respetiva discussão são apresentados no artigo da secção 5.3 (Meneses *et al.*, 2016b). De uma forma geral, evidencia-se a tendência para o aumento da área urbana e a acompanhar esta tendência apresenta-se também o aumento de determinados PQA, sobressaindo o aumento de coliformes fecais, o total de sólidos suspensos, ou mesmo a carência bioquímica de oxigénio a cinco dias (BOD5). Também neste caso se evidencia a necessidade de criar áreas restritas à urbanização, sobretudo em torno dos principais corpos de água, como é o caso da albufeira de Castelo de Bode.

Os incêndios florestais também têm diversas implicações ambientais, sendo uma delas a alteração das propriedades físico-químicas da água devido ao arrastamento através da escorrência superficial de diversos elementos ou compostos resultantes da queima da vegetação durante os incêndios florestais. As cinzas depositadas na superfície dos solos após o incêndio ficam disponíveis para mobilização através de vários agentes: o vento e a água. No caso do arrastamento das cinzas pela água que escorre superficialmente, grande parte vai terminar nos cursos de água e assim serão transportadas para os principais corpos de água, podendo em determinadas concentrações causar a degradação da qualidade da água. Neste sentido, as primeiras chuvas capazes de gerar escoamento superficial são fundamentais para o arrastamento destas cinzas.

No artigo que se apresenta na secção 5.4 (Meneses *et al.*, 2019b) aborda-se esta questão da alteração das propriedades físico-químicas da água após a ocorrência de incêndios florestais na bacia hidrográfica do rio Zêzere. Neste caso também se dividiram setores em função da localização dos principais corpos de água e com estações da qualidade da água. Os resultados apresentados neste artigo demonstraram a ligação, enquanto causa-efeito, entre a ocorrência dos incêndios florestais e a alteração das propriedades físico-químicas da água. Devido à importância da determinação das implicações anteriormente referidas na qualidade da água, é relevante haver cartografia de UOS atualizada, mas é fundamental que esta represente as áreas ardidas o mais próximo da realidade possível para se avaliar a real dimensão deste problema ambiental, pois a ausência de parte desta informação espacial ou delimitação deficitária destas áreas pode resultar na desvalorização de um problema que se tem agravado ano após ano, sobretudo em bacias hidrográficas fortemente afetadas por incêndios florestais. A grande extensão de área ardida resultante dos grandes incêndios que ocorreram no ano de 2017 em Portugal, sobretudo na Região Centro (onde se localiza a bacia hidrográfica em estudo), culminou na perda de qualidade da água de diversos rios e albufeiras (facto referido por diversos meios de comunicação social), causando constrangimentos socioeconómicos e ambientais, por um lado no abastecimento de água potável às populações, por outro nas implicações na fauna e flora dos cursos de água poluídos. Para minimizar estes efeitos após os incêndios, várias ações têm sido desenvolvidas nas áreas ardidas de forma a evitar perda de solo por erosão hídrica e o arrastamento de contaminantes resultantes do incêndio, por exemplo, a aplicação de palha sobre as mesmas (Bento-Gonçalves *et al.*, 2013), a criação de barreiras naturais (como se apresenta no artigo da secção 5.4), a construção de valas de drenagem ou retenção das águas de escorrência superficial, entre outras.

Para o estudo da variação da qualidade da água é fundamental a existência de dados sobre os determinados parâmetros. Desta forma, é fundamental a existência de estações de qualidade da água, seja nos corpos de água mais importantes (albufeiras de determinadas barragens), seja nos rios ou ribeiras que drenam para os mesmos. Atualmente, em Portugal está-se perante um desinvestimento nesta rede de estações, o que compromete seriamente a realização de estudos iguais ou semelhantes aos que se apresentam nesta tese, sobretudo com dados mais recentes. Neste sentido, é fundamental a existência de uma rede de estações coesa para se avaliar o *stress* hídrico (qualidade da água) causado pelas atividades antrópicas ou outras ocorrências, como os incêndios florestais.

5.2. Artigo - Meneses, B.M.; Reis, R.; Vale, M.J.; Saraiva, R. (2015) - Land use and land cover changes in Zêzere watershed (Portugal) - water quality implications. Science of the Total Environment, 527-528, pp. 439-447.

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Land use and land cover changes in Zêzere watershed (Portugal) — Water quality implications

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HIGHLIGHTS

- LUCCs for artificial soils constitute a reduction factor of water quality.
- The wastewater drainage into watercourses is an aggravating factor of water quality.
- Forestry areas in upstream of the dams have higher importance to water quality.
- Maintenance and preservation rules are important to the improvement of water quality.

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ABSTRACT

To understand the relations between land use allocation and water quality preservation within a watershed is essential to assure sustainable development. The land use and land cover (LUC) within Zêzere River watershed registered relevant changes in the last decades. These land use and land cover changes (LUCCs) have impacts in water quality, mainly in surface water degradation caused by surface runoff from artificial and agricultural areas, forest fires and burnt areas, and caused by sewage discharges from agroindustry and urban sprawl. In this context, the impact of LUCCs in the quality of surface water of the Zêzere watershed is evaluated, considering the changes for different types of LUC and establishing their possible correlations to the most relevant water quality changes. The results indicate that the loss of coniferous forest and the increase of transitional woodland-shrub are related to increased water's pH; while the growth in artificial surfaces and pastures leads mainly to the increase of soluble salts and fecal coliform concentration. These particular findings within the Zêzere watershed, show the relevance of addressing water quality impact driven from land use and should therefore be taken into account within the planning process in order to prevent water stress, namely within watersheds integrating drinking water catchments.

1. Introduction

The study of land use and land cover changes (LUCCs) has been developed in recent times in many countries (e.g. Portugal, Spain, France, and others), mainly to understand the impacts of these changes in the territory, in the economy and in the environment and also and mainly to understand the implications on achieving sustainability within development strategies.

These LUCC studies include those that analyze the implications on water resources (Zhang et al., 2014), in particular to understand the cause–effect of these LUCCs in the reduction of water quality and the implications on hydrological processes (Vale, 2002; Seeboonruang, 2012; Warburton et al., 2012; Erol and Randhir, 2013).

The land use and land cover (LUC) and water resources are linked (Vale and Painho, 1999; Gyawali et al., 2013). Water stress is influenced by LUC type in a certain area and from the intensity of use that each type of LUC requires, namely the surface water quality and quantity variation is highly correlated with inadequate anthropogenic practices or vegetation cover degradation processes (e.g. forest fires) (Wang, 2001; Casalí et al., 2010; Hong et al., 2011; Meneses, 2013; Smith et al., 2013).

On the other hand, water bodies reflect these LUCCs, especially when there is a reduction in water quality resources, in many cases caused by population growth, industrial expansion, land use conflicts and/or changes in land management policies (Ahearn et al., 2005; Mouri et al., 2011; Teixeira et al., 2014; Vale and Saraiva, 2012; Valle Junior et al., 2014b, 2015a).

Soil erosion is among the causes of reduction of water quality due to the amount of sediment that arrives to the watercourses and to water reserves (Nunes et al., 2011; OEH, 2012; Meneses, 2014). This is quite relevant in regions where land use intensity combined with land

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occupation type is not in line with soil capabilities (Pacheco et al., 2014; Valle Junior et al., 2014a).

Chemical substances dragged by runoff, depending on their concentration in water, can also reduce water quality (Mouri et al., 2011; Wan et al., 2014). This contamination can also occur if there is leaching of these chemical elements or compounds by sub-surface runoff and the same also arrives in water reservoirs (Valle Junior et al., 2014b).

Due to the shortage of this natural resource in certain places and the high cost associated to water treatment, it is necessary to identify pollution sources, in order to prevent certain types of contamination or deterioration (Meneses, 2013; Yu et al., 2013).

Watersheds that include relevant water catchments used for domestic, agricultural and industrial purposes, require an efficient and well balanced LUC planning, that minimizes negative impacts of certain types of LUC or LUCCs on water, in terms of quality decrease and quantity captured and retained in the soil, or generally available in rivers, lakes or dams (Vale, 2002). In complement, municipalities should account for the intrinsic vulnerability of groundwater reservoirs (Pacheco et al., 2015; Pacheco and Sanches Fernandes, 2013) in their territorial management plans (Valle Junior et al., 2015b).

In the context of LUCCs, guidelines have emerged, most notably in the definition of places to be protected. Providing information from these places and their manipulation by all actors, is increasingly important for the creation of services and new opportunities. These areas are the so-called Smart Regions, that involve public bodies, researchers, companies (also small and medium enterprises) and citizens, following the Linked Open Data orientations currently in implementation (Bauer and Kaltenböck, 2012; Charvat et al., 2014; Dimou et al., 2014; Vale et al., 2015).

2. Main objectives

In this research LUCC assessment was performed using the CORINE land cover (CLC), and water quality variations assessment using water quality data from automatic water sampling stations in a network under governmental supervision.

The main goal of this research is the assessment of the impact of LUCCs in the quality of Zêzere surface waters. Other objectives are as follows: to relate LUCCs with water quality data; to demonstrate the usability LUCC methods in assess of waters impacts in different sectors of a watershed, in this case Zêzere watershed. These techniques can be seen as complementary to identify the potential areas that contribute the most to water quality degradation.

3. Research area

The study area is the Zêzere watershed (area covering 5063.9 km^2), where some of the most important dams of Continental Portugal are located, namely the Castelo de Bode Dam (Fig. 1). This dam supplies drinking water to Lisbon and Western regions of the country covering around ¼ of the Portuguese population. The main watercourse of this watershed is the Zêzere River, it flows into the Tagus River and has as tributaries the Nabão and Unhais rivers.

In the basin upstream sector cambisols predominate, with small areas of fluvisols along the Zêzere River and rankers in the Northwest. The center of the basin is characterized by the predominance of lithosols, with some areas of cambisols. In downstream areas of the basin there are areas of lithosols interleaved with cambisols and luvisols (soil map of Portugal).

The north of study area is located at the Estrela Mountain (Serra da Estrela), with the maximum elevation of 1993 m. Here the annual average precipitation exceeds the 1500 mm (data of Covilhã meteorological station: 1948–2005), while in the areas to the south (minimum elevation 20 m), rainfall is lower (783 mm obtained by data of Tomar meteorological station: 1948–2005).

4. Data, tools and methods

4.1. Water quality data

In the area of study there are automatic stations (St) which register certain water related chemical and physical parameters. These and

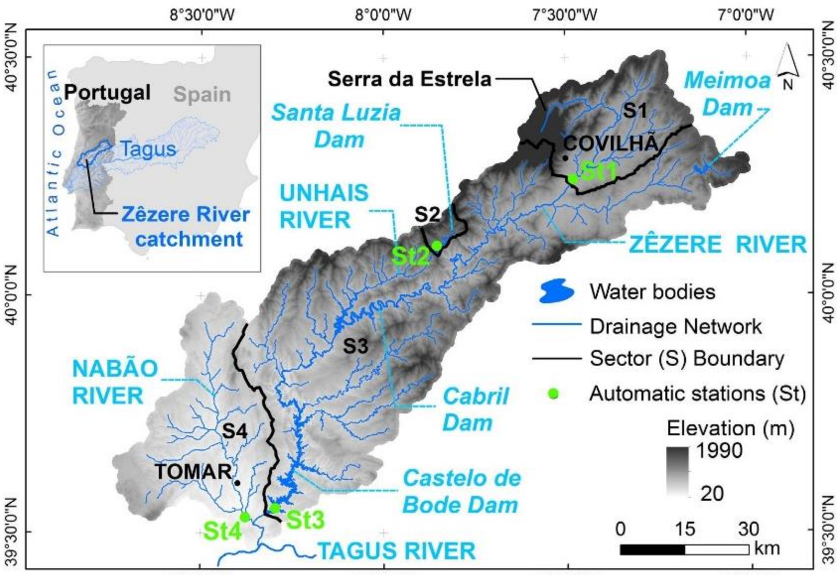

Fig. 1. Zêzere watershed (study area).

other data, obtained in laboratory, are available at the National System of Hydrological Resources (SNIRH), Portugal. The description of the methods used to determine the physical–chemical parameters (SMEWW, ASTM and others referred in Portuguese legislation) are also available at this site, SNIRH.

This study integrates data of automatic stations located in the reservoirs of the main dams and rivers of the Zêzere River basin. Considering that some of the water monitoring stations have been closed introducing discontinuity in water quality time series, the basin was subdivided in four sectors (S) (Fig. 1) and the stations located downstream, representing a more consistent data collecting period have been chosen.

The water quality parameters (WQPs) selected by data available at these stations are as follows: pH, total ammoniacal nitrogen (TAN), 5-day biochemical oxygen demand (BOD5), fecal coliforms (FCs), total coliforms (TCs), electric conductivity in field (20 °C) (EC), total nitrate (NO_3^-) and total nitrite (NO_2^-).

4.2. Land use and land cover data and analyses

The cartography of LUC selected for this study was the CLC of 2000 and 2006 available from the General Directorate for Territorial Development (DGT). This information is divided into several classes that are disaggregated using three levels, the last level being the most detailed. This detailed level includes 44 classes, the most disaggregated level of CLC. The basin limit used to clip CLC information was extracted automatically (through hydro-processing tools of ILWIS 3.31) of the Digital Elevation Model of Europe (GMES RDA project) made available by the European Environment Agency (EEA). The area occupied by water bodies and drainage network (vector data) was obtained from SNIRH, this information being a data complement from CLC.

To perform the LUC area variation analyses the following equation was used:

$$A = A_{t2} - A_{t1}. \quad (1)$$

In Eq. (1), A represents the change of area in absolutes terms, A_{t1} represents the area of a land use type at t_1 and A_{t2} represents this land use area at instant t_2.

Hong et al. (2011) presents a methodology to calculate the area change rate for each LUC. This rate refers to the specific value of the differential value of the area in the initial period for a land use type in two different periods, and it is calculated using following formula:

$$A = \frac{A_{t2} - A_{t1}}{A_{t1}} \times 100\%. \quad (2)$$

In Eq. (2), A_i represents the rate of change of the LUC, A_{t1} represents the area of a land use type at t_1 and A_{t2} represents the area of this land use type at t_2.

The analysis of LUCCs is supported by creating the transfer matrix (Shi et al., 2000; Zhang et al., 2014):

$$A_{ij} = \begin{vmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{vmatrix}. \quad (3)$$

In Eq. (3), A_{ij} refers to the changed area from the i type of LUC for period k to the j type of LUC for the period $k + 1$, and n is the number of LUC types.

4.3. Statistical analyses

For the sectors (S) integrated in the Zêzere watershed the area of each type of LUC was calculated, and combined statistical analyses (descriptive and analytical) using the physical and chemical indicators of water quality were performed.

Statistical tools were used to perform a cluster analysis of water quality using data collected at all stations located in the different sectors, with emphasis on multivariate exploratory techniques.

Factor Analysis was used for exploratory purposes, i.e., was used to detect and identify groups of interdependent categories of land cover changes combined with WQP concentrations for all sectors. This is a statistical method used to study the dimensionality of a set of variables, i.e., this method allows the reduction of the number of variables and also to detect structure in the relationships between variables (Clapham and Nicholson, 2013).

To identify similar behaviors between the LUCC and WQP variations for grouping the sectors, was used an Hierarchical Cluster Analysis. This statistical method is used to identify relatively homogeneous clusters of classes, based on measured characteristics (Burns, 2009). The sector groups were obtained using Euclidean distances (single linkage).

The software used in these evaluations was Statistica 7. All data (LUC and WQP) were previously standardized.

The WQP values that were used in these evaluations are the annual averages for 2000 and 2006, obtained using SNIRH available data.

5. Results of the analyses

5.1. Land use and land cover distribution and changes between 2000 and 2006

The predominant LUC for the study area are forest and semi natural areas representing more than 72% of the total area (Fig. 2) located mostly in the watershed central sector (Fig. 3). This type of LUC include the major changes, mainly coniferous forest and mixed forest to transitional woodland-shrub, resulting from forest fires and deforestation, occurred over the last two decades (Meneses, 2013).

Approximately 25% of the LUC area is agricultural land, being this type of LUC more representative upstream and downstream of the watershed, where the complex cultivation patterns and land mainly occupied by agriculture stand out, mixed with significant areas of natural vegetation (more than 7% each). This LUC type (agricultural land) decreases between 2000 and 2006. These results can be explained by high losses or transitions that occurred mainly in soils occupied by complex cultivation patterns to discontinuous urban fabric and transitional woodland-shrub. However, there was another type of dynamics in the agricultural class, i.e., in a vast part of non-irrigated arable land the transitions occurred increasing permanently irrigated land due to the availability of water in the reservoirs (APA, 2002; Vale, 2002; Gregório et al., 2011) which allowed the increase of this type of land use.

The artificial surface areas represent the most relevant growth registered between 2000 and 2006 (0.1% of the total area). Analyzing in detail the area variations within this class type of LUC, the expansion of discontinuous urban fabric (0.03%) stands along with industrial or commercial units (0.09%). These artificial surfaces intersperse the

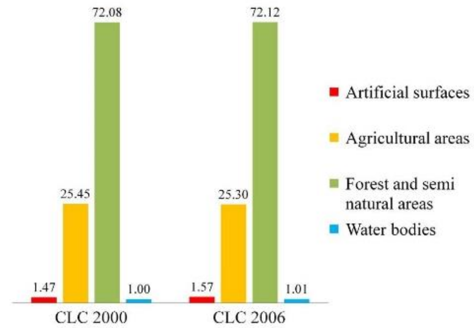

Fig. 2. Area (%) by principal types of LUC in Zêzere River basin.

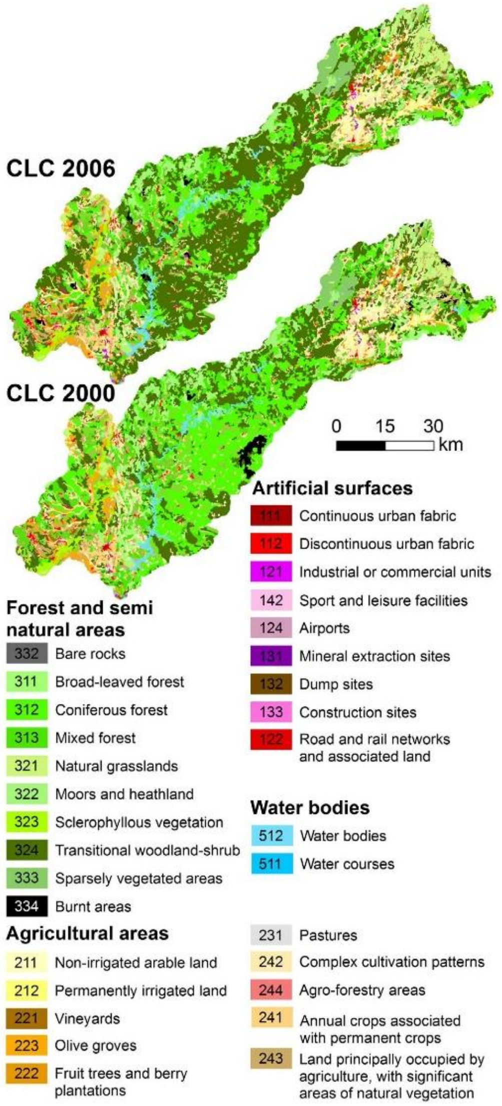

Fig. 3. Land cover in Zêzere watershed (CLC 2000 and 2006).

agricultural areas and are located very close to the main watercourses of this watershed. In parallel with this discontinuous urban fabric increase arose the appearance of motorized recreation services in the main water reservoirs (APA, 2002).

The water bodies occupy approximately 1% of the total area, including the main water courses identified in CLC data.

The analysis of the LUCCs by sectors (Table 1), points out, in general terms, the high loss of area in the class of coniferous forest, with higher losses especially in intermediate sectors (S3 and S4). For some classes of CLC presented in this study no area changes between 2000 and 2006 were registered.

The LUC transition tables for each sector (Tables 4, 5 and 6 in the supplementary data) show that the main transitions of this type of LUC went into transitional woodland-shrub, hence this class has a high increase in area between 2000 and 2006. Forest fires have also contributed to forest cover reduction, especially in resinous forest in the first years of the 2000 decade. In 2006 these degraded land cover classes include the transitional woodland shrub-class.

In these sectors also stands out the reduction of non-irrigated arable land, due to the transition to permanently irrigated land and vineyards. These cultures lead to permanently irrigated land and require the availability of water in quantity and quality and may induce water stress.

Land productivity maximization leading to agrochemicals use increase, may lead to contaminants increase (e.g. pesticides and herbicides, heavy metals, sulphides, cyanide, dioxins, organic matter, etc.) in water when they are dragged by runoff or lost through leaching. In this case, contamination is understood as the introduction or presence of above-normal quantities of compounds in the waters and may or not affects the organisms that inhabit in the ecological system or that depend of this natural resource.

5.2. Water quality Indicators

To relate LUC with water quality changes, water quality parameters were selected and monitored for the same time period. Table 2 presents the major differences between the upstream sectors of the watershed (S1), intermediate sector (S2 and S3) and downstream sector (S4) synthesizing the registered values for these selected parameters.

S4 stands out from the other sectors, because of the highest values of WQPs, with exception for BOD5 in S1 registered for 2006. In this sector it was observed high TC increase between 2000 and 2006 and also increase of TAN, FC, EC, NO_2^- and pH. In S1 the registered values for WQPs are very high, but there is a decrease between the two years considered, with the exception of TAN and BOD5.

In S2 and S3 the lower values of WQPs in the dam water body were observed, however there was an increase in BOD5, EC, NO_3^- and pH. In S3 both FC and TC registered an increase, indicating a water quality deterioration tendency.

Although there are variations in the values of WQPs previously presented they are within the legal limits, according to the Portuguese regulation, with two exceptions: fecal coliforms (that should be 0), total coliforms and NO_3^- in sector 4 with 0.99 mg L^{-1} in 2006 (maximum allowable 0.5 mg L^{-1}) (Fig. 4).

5.3. Variations of water quality and land use land cover changes

From the year 2000 to the year 2006, and considering available data included in Table 2, water quality in the sectors considered in the Zêzere watershed suffered a decrease. The combined analysis of WQP result variations and CLC area class changes (Table 3), both registered during the period mentioned above, allowed us to identify similarities that can, in some extent, explain the impacts of LUCCs in bodies of water in the study area.

The variation of TAN has high positive correlation with changes in area occupied by permanently irrigated land and vineyards, being these types of LUC frequently associated with diffuse pollution sources within water bodies.

This pollution, causing water quality degradation, probably result from excessive use of chemicals in soils for the increase of agricultural production, that induce a greater availability of NH_4+ and NO_3^- (nitrogen minerals forms in greater quantity in soils, Cordovil, 2004) and its easy mobilization by the waters drained from these areas, where the agricultural practices favoring fast flow, thereby reducing losses by volatilization and the consequent increase of concentrations of these mineral forms of nitrogen in downstream waters.

However, the variations of de NO_3^- are also correlated with the variations of natural grasslands, type of land cover with increased area in sector 3 (S3) where the main dams in the water watershed are located. The increased area of natural grasslands in this sector is the result of transitions from soils originally occupied by coniferous forest.

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Table 1
Most significant LUCCs in sectors of Zêzere watershed (values in bold). Area of transitions (ha) by class CLC 2000 and 2006. For the ID CLC correspondences see Fig. 3.

	Sectors and total area		CLC 2006					
		ID	221	222	311	312	313	324
CLC 2000	S1 (70,055 ha)	242	**30.1**	**42.6**	0	0	0	0
		312	0	0	0	3948.7	62.5	**1457.3**
		313	0	0	3.5	0	3354.4	**990.3**
		324	0	0	189.7	**360.6**	0	13,903.9
	S2 (4937 ha)	312	0	0	0	423.6	0	**977.0**
		313	0	0	0	0	37.8	**135.2**
		324	0	0	0	**26.7**	0	2036.1
	S3 (321,453 ha)	311	0	2.4	14,637.4	180.5	151.2	**7258.4**
		312	0	0	94.6	55,011.4	121.2	**55,960.3**
		313	0	7.8	55.0	118.4	20,375.2	**6631.2**
		324	0	7.4	**4376.8**	**6385.9**	**1381.6**	63,598.8
		334	0	0	0	0	39.6	**4822.7**
	S4 (109,941 ha)	311	0	0	4204.1	0	68.2	**2488.0**
		312	8.0	0	37.0	7890	44.0	**4369.4**
		313	0	0	79.3	11.9	10,111.2	**5196.9**

In the case of variations of NO_2^- the highest correlation of this parameter is related with changes in area occupied by dump sites, mineral extraction sites and olive groves; a significant correlation is also found between changes of area from these types of LUC and variations of TC.

Changes of FC concentrations have positive correlation with changes of area occupied by pastures, non-irrigated arable land, road and rail networks and associated land. EC variations already have high correlations with changes of area occupied by transitional woodland-shrub and water bodies.

The variation of BOD5 concentration is correlated positively with changes of area occupied by construction sites, permanently irrigated land, broad-leaved forest and mixed forest.

A high positive correlation was verified between the pH variations and the changes in land area occupied by fruit tree and berry plantations, complex cultivation patterns and transitional woodland-shrub.

6. Discussion

The LUCC analysis in association with changes in water quality parameters, point out the strict relation between water and land use management. The present study, in particular points out the most important LUC classes in terms of their contribution for water quality changes in the Zêzere River watershed (Fig. 5).

The TAN presented variations similar to variations of irrigated land and permanent vineyards. The results seem to reflect the influence of

Table 2
Statistical description of data for water quality parameters in the sectors (S) of Zêzere watershed.

Sector	Year		TAN	BOD5	FC	TC	EC	NO_3^-	NO_2^-	pH
			($mg\ L^{-1}\ NH_4^+$)	($mg\ L^{-1}$)	($MPN\ 100\ mL^{-1}$)		($\mu S\ cm^{-1}$)	($mg\ L^{-1}$)		
S1	2000	Max.	1.1	6.8	11,000	11,000	647.0	9.2	0.41	7.6
		Min.	0	0.8	21.0	150	40	3.1	04	6.6
		Average	0.5	3.3	3359.1	3980.9	122.2	5.9	0.12	7.1
		St. Dev.	0.4	2.0	4240.4	4566.1	167.0	1.9	0.12	0.3
	2006	Max.	7.1	28.0	2280	2530	283.0	7.3	0.23	8.5
		Min.	0.2	3.0	200	250	48.0	2.0	02	6.7
		Average	0.9	6.7	663.8	1010	103.0	4.0	07	7.0
		St. Dev.	2.1	7.8	644.7	853.7	73.1	1.7	07	0.5
S2	2000	Max.	0.8	1.7	48.0	110	39.0	6.0	03	7.6
		Min.	0	0.2	2.0	2.0	23.0	0.2	00	6.6
		Average	0.3	1.0	12.3	39.0	27.2	1.3	01	7.1
		St. Dev.	0.3	0.5	16.6	42.3	4.8	1.5	01	0.4
	2006	Max.	0.2	4.0	50	71.0	40	3.1	02	8.7
		Min.	0.2	3.0	0	0	26.0	2.0	02	6.7
		Average	0.2	3.2	10.6	28.8	33.0	2.2	02	7.2
		St. Dev.	0	0.4	16.3	28.6	4.0	0.3	00	0.5
S3	2000	Max.	0.2	5.7	122.0	2000	85.1	2.7	02	7.8
		Min.	0	2.0	0	6.0	51.8	0.6	01	6.2
		Average	0.1	2.4	21.5	320.7	76.6	1.7	02	7.1
		St. Dev.	0	1.1	38.8	640.8	9.7	0.6	00	0.5
	2006	Max.	0.1	3.7	340	4300	184.0	2.6	04	8.4
		Min.	0	3.0	0	8.0	68.3	1.1	01	7.7
		Average	0	3.1	60.5	503.2	90.7	2.0	02	8.0
		St. Dev.	0	0.3	119.9	1204.9	41.7	0.6	01	0.4
S4	2000	Max.	1.6	10.6	100,000	270,000	543.0	40.4	0.54	8.1
		Min.	0.1	2.7	6300	36,000	310	2.8	05	7.3
		Average	0.6	4.4	48,091.7	188,666.7	467.0	9.3	0.19	7.7
		St. Dev.	0.5	2.2	31,846.8	132,307.7	71.4	10	0.14	0.2
	2006	Max.	3.2	10.6	400,000	17,000,000	670	10	0.99	8.0
		Min.	0	3.0	800	80	339.0	5.6	05	7.2
		Average	0.7	4.4	48,100	1,492,390	506.9	7.4	0.29	7.6
		St. Dev.	1.0	2.1	111,808.0	4,884,199.9	97.2	1.4	0.29	0.2

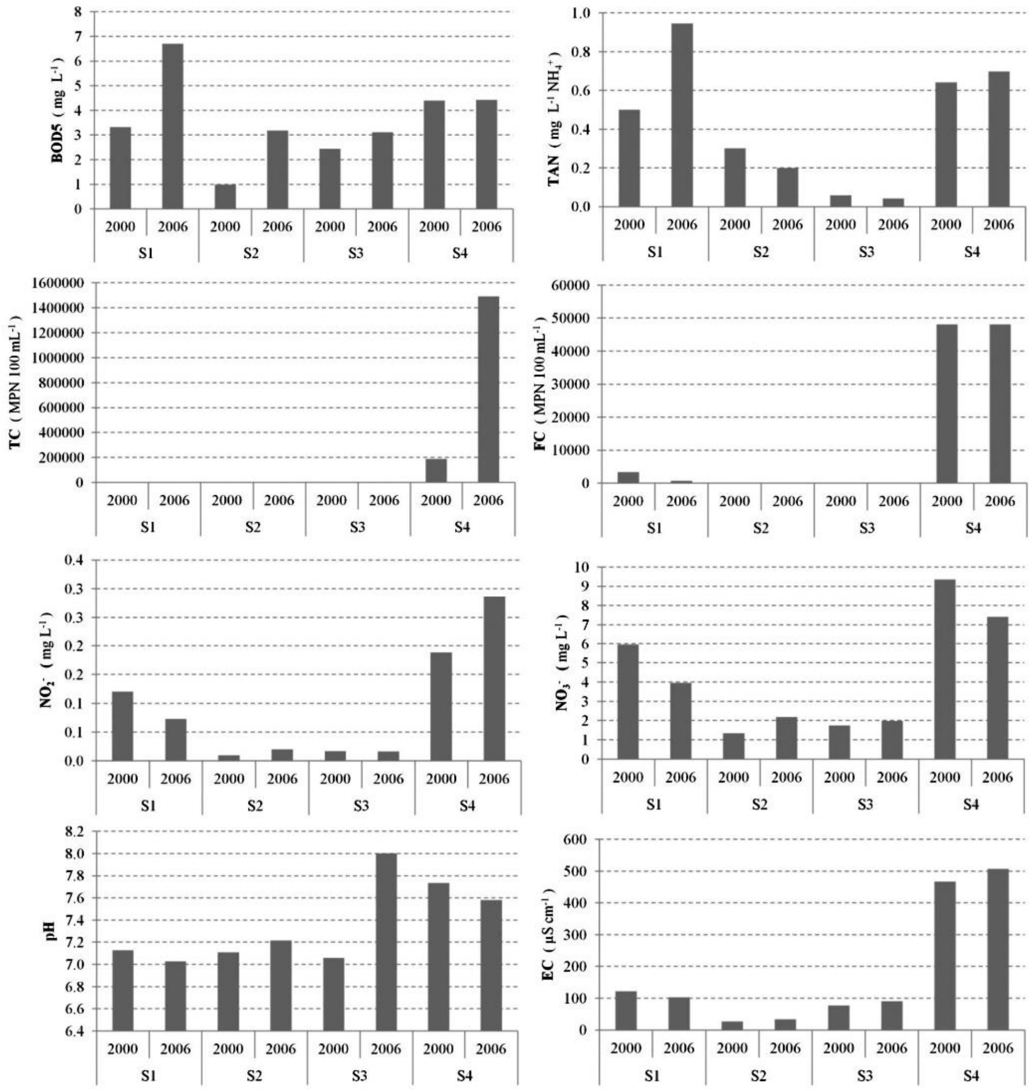

Fig. 4. Annual average of WQPs (years 2000 and 2006) for the four sectors.

drained waters from these soils to streams or water reservoirs inducing consecutive changes on these waters chemical composition. Some studies point the increase of TAN influenced by irrigated areas (e.g. Howden, 2012), in some cases derived from anthropogenic practices used in arable lands, such as irrigation of animal manure (Chastain and Montes, 2005), while other studies refer the interference of increased population and settlements as being the most responsible for the variation of TAN in surface waters, although in some cases the interference of these last two factors is negligible due to the low input of ammoniacal nitrogen in surface water but also due to the high water quality and water regeneration capabilities in the locations where the studies were carried out (Vushe et al., 2014).

BOD5 variations are also linked to the aforementioned LUC variations. In this case the variation has a very high relation to mixed forest variations, and this area decrease is in line with previous statements for this type of LUC and it is relevant in inducing water quality preservation. In some cases the increase of BDO5 moreover associated with artificial areas increase related to industrial activities (Yévenes et al., 2015). BDO5 variations observed in this study have high positive correlation with changes of the area of construction sites, and this might result from the increase in urbanized land.

Considering the Zêzere watershed, Vale (2002) also observed in his doctoral research that the BOD5 increase between 1991 and 1999, establishing some possible implications of land-use planning practices in this watershed, referring in particular the increase of water deterioration pressure from non resident population, and urban sprawl, and the consequent increase of sewage waters drained into the reservoirs of this watershed.

The expansion of artificial areas (including urban sprawl, infrastructures and recreation activities) compromising mixed forest areas also

Table 3
LUCC (CLC 2000–2006) and WQP variations in Zêzere watershed – Correlation coefficients (significance level $p < 05$).

CLC (ID)	TAN	BOD5	FC	TC	EC	NO_3^-	NO_2^-	pH
112	−02	−0.55	0.19	07	0.28	−06	05	0.73
121	−0.20	−0.88	0.44	0.64	0.76	−0.29	0.63	0.33
122	−0.32	−0.94	0.56	0.78	0.89	−0.27	0.79	0.19
131	−0.14	−0.73	0.37	1.00	0.85	−0.53	0.92	−0.38
132	−0.11	−0.68	0.33	1.00	0.81	−0.56	0.91	−0.46
133	0.23	0.86	−0.47	−0.95	−0.90	0.44	−0.91	0.15
211	−0.59	−0.37	0.59	0.58	0.62	0.14	0.75	−0.48
212	0.95	0.81	−0.99	−0.27	−0.77	−0.61	−0.62	−0.52
221	0.99	0.72	−0.99	−0.19	−0.70	−0.70	−0.57	−0.49
222	−0.10	−0.23	0.13	−0.43	−07	0.33	−0.34	0.94
223	−0.11	−0.68	0.33	1.00	0.81	−0.56	0.91	−0.46
231	−0.88	−0.67	0.90	0.50	0.80	0.42	0.80	−03
241	0.31	−0.27	−0.12	0.89	0.45	−0.82	0.64	−0.77
242	09	0.21	−0.16	−0.77	−0.49	0.40	−0.71	0.83
243	0.24	0.43	−0.31	0.26	−0.14	−0.34	0.14	−0.95
311	0.39	0.83	−0.57	−0.30	−0.63	−0.10	−0.40	−0.70
312	0.31	0.45	−0.37	0.27	−0.16	−0.40	0.12	−0.96
313	0.24	0.88	−0.48	−0.58	−0.74	0.21	−0.59	−0.41
321	−0.89	−0.79	0.93	0.14	0.68	0.64	0.48	0.70
322	0.50	0.47	−0.52	0.31	−0.21	−0.59	08	−0.99
323	−0.25	−0.88	0.49	0.92	0.91	−0.41	0.89	−08
324	−0.32	−0.51	0.40	−0.19	0.23	0.35	−05	0.94
334	0.23	0.24	−0.23	0.48	06	−0.47	0.34	−0.98
512	−0.25	−0.89	0.49	0.92	0.91	−0.41	0.89	−08

occurred in these mixed forest areas, may be related to water quality decline, hence the reduction in the mixed forest area presents a high relation with BDO5 variations observed in this research.

FC variations are very similar to the ones described above for industrial or commercial units, indicating a high increase in anthropogenic artificial area within this time period. The increase of areas covered by roads, rail networks, and discontinuous urban fabric, are also very similar reflecting in this case the deficient domestic sewage drainage network and an easy access to waterways for recreational activities with higher risk regarding water degradation. Soils for pasture (pastures lands and natural grasslands) may induce FC increase; the lack of obstacles to runoff (namely forestry) may lead to greater transport capacity raising FC concentration in downstream watercourses water.

Forest fires and subsequent burnt biomass, are also quite relevant for immediate and subsequent water quality deterioration. Meneses (2013) and Meneses and Cortez (2015) also observed this interference in watershed of São Domingos Stream (east of study area) after a forest fire that proportioned the variation of physicochemical properties of the water.

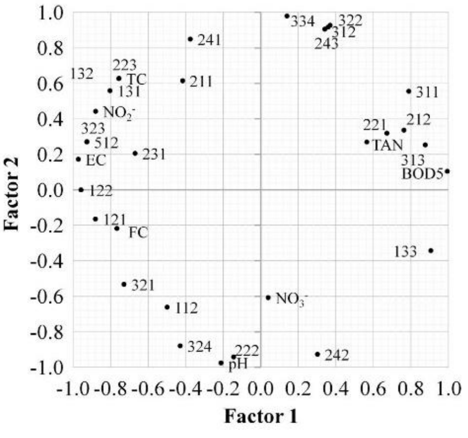

Fig. 5. Results of the factor analyses of LUCC (ID CLC) and WQP variations.

Considering the area variations by type of LUC derived from LUCCs and the variations of several WQPs (BDO5, FC, TC and NO_2^-), between 2000 and 2006, similar behavior was observed between S1 and S2, which is reflected in the analysis of the tree diagrams based on Euclidean distances (single linkage), performed with the data from the four sectors considered for the study area (Fig. 6).

The S1 and S2 sectors are located upstream of the sub-basins that comprise the Zêzere River basin, include areas with high altitude and with reduced anthropogenic interference (reduced artificial surfaces area), where there were no high LUCCs. Besides a wastewater treatment stations has been built in S1, during this time period, factor which may explain the reduction of some WQP values (e.g. FC, TC, EC and NO_3^-).

Analyzing the Euclidean distances, S4 stands out from all the sectors with the largest distance. In this sector a high increase of artificial surfaces was observed, especially the increase of soil occupied by industrial or commercial units and discontinuous urban fabric. This sector is also largely used for agricultural practices (especially in luvisols), using natural fertilizers but mainly chemical fertilizers, to increase agriculture productivity. This fact may largely be responsible for high concentrations of FC, TC and EC in the waters of Nabão River.

The FC and TC concentration increase in waters of S4 can be also explained by the increase of livestock farms combined with the deficient sewage network, in some cases drained directly to the Nabão River, fact that has been namely reported by the media. The increase of these WQPs is described in other studies (e.g. Folletto et al., 2014; Plessis et al., 2014), having identified these same factors as the cause for water quality degradation. Integrating this watercourse (S4), where the largest increase in artificial surfaces was registered, particularly for industrial or commercial units, water quality decrease was higher in the Nabão River.

This watercourse is the less important in terms of extraction of drinking water, nevertheless for drinking water quality preservation, recovering water quality of rivers has been established as a main goal of EU policy and water preservation of rivers upstream are important considering runoff and contamination risk downstream and ground water reserves preservation.

WQP values reflect the dissolution of the various substances including chemical compounds in water bodies, but mainly in the sampling stations surroundings and namely where water samples (except S4) were collected.

WQP values may vary in watercourses depending on the proximity to the pollution source, hence the importance of monitoring the quality along water courses, must be in line with pollution risk.

The largest drained area of the Zêzere watershed and two reservoirs (Cabril and Meimoa) are integrated in sector S3. Being so, the values in this sector tend to increase not only due to greater area of agricultural

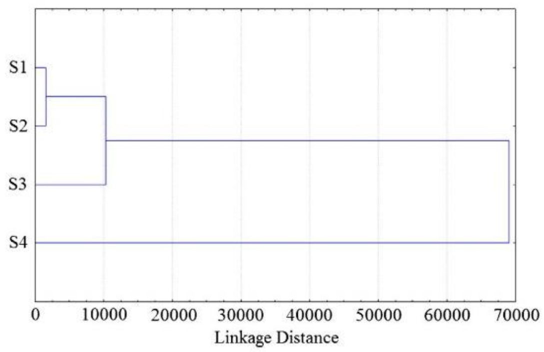

Fig. 6. Sector dendrogram, integrating LUCC and WQP variations.

soils and larger areas of high anthropic use, but also due to high increase of transitional woodland-shrub and forest fires. These two factors may explain the distinction of this sector from the cluster formed by S1 and S2.

Considering all this results it can be stated that LUCCs identified have interference in the quality of surface water of the Zêzere watershed. This stands out from the sector analysis of this watershed namely associated to (1) the increase of soil artificialization (emphasis on the increase of industrial units), (2) conversion of forest land and (3) development of inappropriate agricultural practices on soils previously occupied by forest or shrub, type of coverage that contributed to the maintenance of water quality.

This LUCC, if not in line with water stress concerns, may contribute to water quality degradation that lead, in the short, medium or long terms, to disrupt the development process.

7. Conclusions

The presented work explored the relations between LUCC and water quality within a watershed exploring the unequivocal relation among land use and land cover management and water quality preservation concerns.

The results obtained for the Zêzere watershed point out those water reservoirs with greater forest occupation lead to higher water quality protection. Anthropic actions are the main driving forces inducing land use change.

This is also the case in the presented example: forest occupation transitions to another type of land occupation or use, are mainly derived from anthropic actions. Transitions for agricultural soils or artificial soils induce water stress, increasing the risk of water quality deterioration.

This can be detected in water sampling from increased concentrations of certain elements or chemical substances in soils from anthropic applications (e.g. pesticides and herbicides, heavy metals, sulphides, cyanide, dioxins, organic matter) which become available for entrainment by runoff leading to an increase of their concentrations on water reservoirs.

Wastewater drainage into watercourses, directly or indirectly is also a relevant concern leading to negative impacts on water quality. This fact in the present study results from a high increase in housing namely urban sprawl within superficial water body neighborhood, in the present case the Zêzere waterfront.

Wastewater treatment capacity must be in line with urban growth strategies and urban licensing, preventing contamination risk from sewage treatment breaking is essential. Natural regeneration capacity must be present in all land use planning development strategies including water contamination risk and treatment costs evaluation and payment mechanisms.

The increased concentration of soluble salts and coliforms registered in the period under analysis reinforce the relevance of relating urban planning with water management and water infrastructures and public investments. Water courses upstream in dams namely in those built with drinking water supply purposes, are those that have higher connection to the drainage of surface and ground waters from the established land uses in upstream sectors, and therefore governments should have, in these soils, a higher concern with land use planning and occupation allowance within these areas.

The maintenance and preservation rules assigned to drinking water capture surroundings, and their effectiveness could significantly contribute to the improve water quality and reduce treatment costs. The intensity of use must also be addressed, especially in soils with anthropogenic intervention (agricultural or urbanized areas), integrating these assessments to a balanced cost/benefit land use planning policy including the definition of sustainable exploitation forms addressing public and private land owners.

Technological improvements used in water treatment require high investments (acquisition and maintenance); in this sense it will be more efficient to act on the areas with the types of land use and land cover that contribute most to the degradation of water quality.

Alongside the creation of preventive and sustainable measures for LUC, in particular the restriction of anthropic uses within the near limits of the water bodies, where drinking water for domestic consumption or industrial activities is collected, will be key factors to properly address water quality, prevent water stress in the near future and assure sustainable water management in a cost effective and efficient way.

Accounting the whole watershed land use and their related water impacts cannot be neglected in building the whole management strategy, integrating land use and water management together in the development strategies assessment, integrating economic growth concerns with preservation.

Appendix A

Equations

$$A = A_{t2} - A_{t1} \tag{1}$$

$$A = \frac{A_{t2} - A_{t1}}{A_{t1}} \times 100\% \tag{2}$$

$$A_{ij} = \begin{vmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{vmatrix} \tag{3}$$

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2015.04.092.

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Urban sprawl in Zêzere watershed (Portugal) and the risk of reduction of the water quality

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Abstract: This paper explores the Land Use and Land Cover Changes (LUCC) in the Zêzere watershed (Portugal) and the risk of reduction of surface water quality, with emphasis in urban sprawl, because the LUCC that took place in the past in this watershed showed the increase of this type of land use and land cover (LUC). This factor resulted in changes in shallow water quality in the main dam reservoir: Castelo de Bode. It was verified a tendency to an increase of urban areas through the analysis of Corine Land Cover (CLC) cartography for 1990, 2000, 2006, and 2012. It has been estimated the probability of urban sprawl in this watershed by bivariate statistical models (Fuzzy Logic-Gamma operator) and, using the previous results, we determined spatially the areas most likely to surface artificialization until 2018 and 2024. These results and the observations of variations of water quality parameters (WQP) in the past will serve to calculate the tendency for WQP variation in future. The results indicate that urban sprawl may increase the risk of deterioration in the quality of surface water.

Keywords: Urban sprawl, Water quality implications, risk, Zêzere watershed.

1. Introduction

Urban sprawl has been indicated as a factor that causes the reduction of water quality in some river basins, particularly that of surface waters (Fiquepron *et al*., 2013; Scatena, 2000; Teixeira *et al*., 2014; Yu *et al*., 2013). In the Zêzere watershed there is indication of implications of urban sprawl in the water quality of the main reservoirs, especially in those rivers where more pronounced process of urban sprawl is observed (Meneses *et al*., 2015; Vale *et al*., 2015). This watershed includes an important water reserve of Continental Portugal, namely the Castelo de Bode dam. This dam is relevant in the national context because it supplies water to the greater Lisbon region (accounting for more than a fifth of the Portuguese population). Anthropogenic interventions in the land use and land cover (LULC) of this watershed have implications with the quality of water stored in the main reservoirs, especially the artificialization of soil for housing construction, roads, or commercial and industrial infrastructures (Meneses *et al*., 2015).

In this context it is necessary to evaluate how urban sprawl influences a decrease in the quality of surface water due to the growing anthropogenic pressures in the catchment areas of drinking water reserves, a problem already discussed in some territories around the world (Fiquepron *et al*., 2013; Glavan *et al*., 2013; Li *et al*., 2008; Scatena, 2000; Vale *et al*., 2015; Vushe *et al*., 2014; Gottfried and Debano, 1983).

Water scarcity and the urban sprawl (without creation of preventive measures of waste water treatment) are two factors that lead to an increase of the risk of surface water quality reduction (Enderlein *et al*., 1996), in particular because urban sprawl provides conditions for an increased input of pollutants or contaminants in surface water.

The availability of water in quantities is also important, particularly in the dilution of the elements or compounds, i.e., a lesser amount of water stored in reservoirs is the cause of an increase in the concentration of certain physical and chemical elements in these waters, thus reducing their quality (Meneses, 2013). Given the importance of this natural resource it is necessary to evaluate the resulting impacts of LUCC in order to minimize interference in its availability (quantity and quality).

2. Main objectives

The main objective of this research is to evaluate the risk of water quality reduction in the Castelo de Bode dam (Zêzere watershed) as a function of the urban sprawl that has occurred in the last two decades. Based on the predictions of surface artificialization in the future determined by bivariate statistical models. The risk of water quality reduction in the future was assessed, considering that the conditions responsible in the past, for the reduction of water quality still remain.

Given the vulnerability of this natural resource to degradation, the hazard resulting from the process of urban sprawl and its consequences on water quality, and bearing in mind the elements mentioned, particularly the population relying on this natural resource, we intended to determine the risk implied by the process of urban sprawl in the reduction of water quality.

3. Materials and methods

3.1 Study area and data

The study area is Zêzere watershed (Potugal), with an area covering 5063.9 Km^2. This watershed comprises one of the main reservoirs of drinking water in Continental Portugal which supplies various municipalities in the Lisbon region (area with the highest population density in the Portuguese territory) (Fig. 1).

For the assessment of urban sprawl, land use and land cover changes (LUCC) were accounted using the Corine Land Cover cartography (CLC 1990, 2000, 2006 and 2012 in Figure 1) and the results obtained were later crossed with the water quality parameters of the Castelo de Bode dam (information provided by National System of Hydrological Resources of Portugal - SNIRH). With the trends of urban sprawl and the variations of the parameters of water quality in the past, it was determined the probability of surface water quality deterioration, assuming the existence of a cause-and-effect relationship that will be determined by establishing correlations with the above mentioned results.

CLC 1990 was used to model the probability of urban sprawl. CLC 2000 and CLC 2006 were used to calibrate the model, and CLC 2012 was used to validate the results.

The natural variables that have integrated this probability modeling of urban sprawl were: slope, elevation, precipitation, humidity, soil type, insolation (hours), distance to main urban centers, and distance to road network.

The water quality parameters (WQP) were selected on the basis of the data available for the stations located in dam reservoir, Castelo de Bode, currently available on the website of the SNIRH. We selected: pH, total ammoniacal nitrogen (TAN), 5-day biochemical oxygen demand (BOD5), fecal coliforms (FC), total coliforms (TC), total mercury (Hg), electric conductivity in field (20 °C) (ECF), total nitrate (NO_3^-), total nitrite (NO_2^-) and total suspended solids (TSS).

The data series of WQP selected lack some data, in this sense we considered the three-year average (year corresponds to the CLC data and the two previous years), admitting that LUCC observed at a given time are also a result of LUCC dynamics that occurred in previous years.

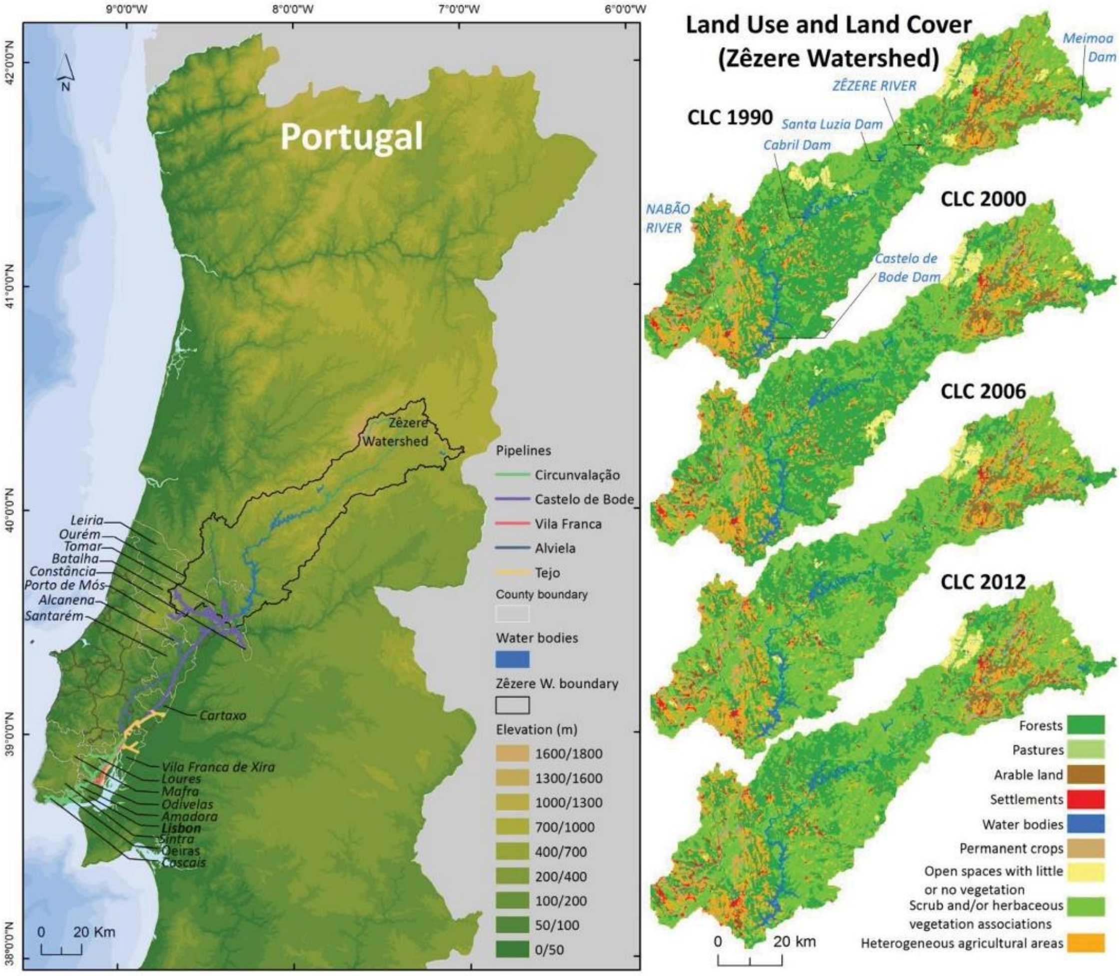

Figure 1 – Land use and land cover of Zêzere watershed in different years (CLC data) and the counties supplied with drinking water of the Castelo de Bode Dam.

3.2 Numerical modelling of the urban sprawl and determination of the risk of reduction of the water quality

The predictions of urban sprawl were determined by a bivariate statistical model. First we crossed urban areas with natural variables and objectively determined the *a priori* probability and conditional probabilities (for each class of independent variables). These results were converted through the *fuzzification* process for further integration of the Spatial Data Modeller (Arc-SDM) in ArcGIS 10.2. The following process was the determination of the probability of urban space sprawl through the *Fuzzy* Logic (*Gamma* Operator in Eq. 1) (Chen *et al.*, 2013; Zadeh, 1965).

$$Fuzzy\ Gamma = \left(1 - \prod_{i=1}^{n}(1-\mu_i)\right)^{y}\left(\prod_{i=1}^{n}\mu_i\right)^{1-y} \quad (1)$$

In Eq. (1), μi is the *fuzzy* association values (i=1, 2, 3, …, n) for the variables 1, 2, 3, …, n; n corresponds to the number of variables considered, and y the parameter set by the operator.

The risk of water quality reduction in Zêzere watershed was evaluated as a function of the probability of urban sprawl, because the increase of this LUC type during the last decade had interference in the quality of surface water (Meneses *et al*., 2015; Vale *et al*., 2015). In this way, the urban sprawl is considered one of the main factors associated with the degradation of the water quality in this watershed.

4. Results and discussion

4.1 LUC transitions of last years and the probability of urban sprawl

The LUCC in Zêzere watershed in the last decades was significant, namely forest transitions to other LUC types. In the case of settlements, the area of this LUC type increased between 1990 and 2012, this being the result of the urban sprawl increase, especially for heterogeneous agricultural areas and forest areas (Table 1).

The high anthropic interventions or activities in Zêzere watershed contributed to the high transitional LUCC area of certain LUC types evaluated in this investigation, namely LUCC for agricultural, grassland and settlements. In this case, the settlements encompass several LUC types: urban fabric; industrial, commercial and transport units; mines, dump and construction sites; and artificial, non-agricultural vegetated areas.

These LUCC have implications on the quality of surface water, on the one hand due to the reduction of infiltration by the soil sealing, which provides greater surface runoff, contributing to increase the level of certain elements and compounds drawn by this water (e.g. suspended solids with physical implications and also in the organoleptic characteristics). On the other hand, population increase lead to the development of human activities in the areas of runoff leading to the dam reservoir, can induce variation of certain WQP, increasing the levels of fecal coliforms, and BOD5, due to poor sewerage and wastewater treatment systems efficiency.

For the period 2012-2018 can be estimated an increase of 9494.5 ha in urban areas and for the period 2018-2024 an increase of 1012.4 ha. Analyzing the results point out an increase in urban areas between 1990 and 2012 (Fig. 2), but analyzing growth trends for the aforementioned periods, we highlight the absolute variations of urban areas with an increase until 2024 (very similar to the one observed between 1990 and 2000), when compared with the increase observed between 2012 and 2016.

Table 1 – LUC changes in Zêzere watershed (area ha) between 1990 and 2012 (CLC data).

CLC 1990 \ CLC 2012	Arable land	Forests	Heterogeneous agricultural areas	Open spaces with little or no vegetation	Pastures	Permanent crops	Scrub and/or herbaceous vegetation associations	**Settlements**	Water bodies	Total
Arable land	14166.5	50.7	1675.9	0	334.8	642.6	487.6	**154.0**	0	17512.0
Forests	131.4	113603.7	1027.4	508.5	8.3	218.5	92775.9	**652.7**	9.8	208936.3
Heterogeneous agricultural areas	2668.8	1079.0	82490.2	0	331.4	3185.4	2264.0	**1408.5**	31.7	93458.9
Open spaces with little or no vegetation	0	4599.8	16.6	8926.7	0	0	5830.7	**0**	0	19373.7
Pastures	50.7	0.5	144.0	0	28.2	0	22.7	**0**	0	246.1
Permanent crops	353.2	10.5	918.8	0	20.1	16102.4	60.8	**238.8**	0	17704.5
Scrub and/or herbaceous vegetation associations	374.4	31907.1	1063.8	219.3	392.5	195.7	103477.4	**347.4**	58.2	138035.7
Settlements	**0**	**1.5**	**30.7**	**0**	**0.2**	**3.1**	**74.1**	**6006.8**	**0**	**6116.3**
Water bodies	0	7.9	1.6	0	0	0	3.0	**0**	4990.0	5002.4
Total	17744.9	151260.6	87369.0	9654.5	1115.4	20347.7	204996.1	**8808.2**	5089.6	506386.1

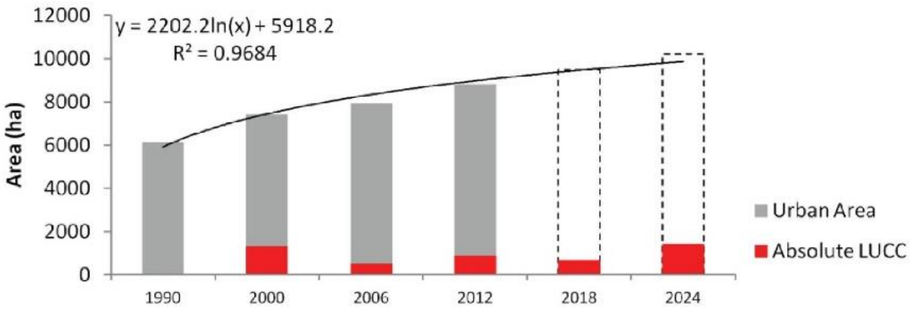

Figure 2 – Urban areas in Zêzere watershed (CLC data) and the projection of urban sprawl to 2018 and 2024.

In Figure 3 we present the findings of the probability of spatial urban sprawl, obtained through the Fuzzy Gamma model. The most probable areas of urban sprawl are located in the Nabão sub-basin. Based on this probability and using the calculation of the trend of increase in urban areas determined from the CLC cartography for different years, because we located the areas that will, with greater probability, be the next ones to be affected by the process of urban sprawl (higher Fuzzy Gamma values).

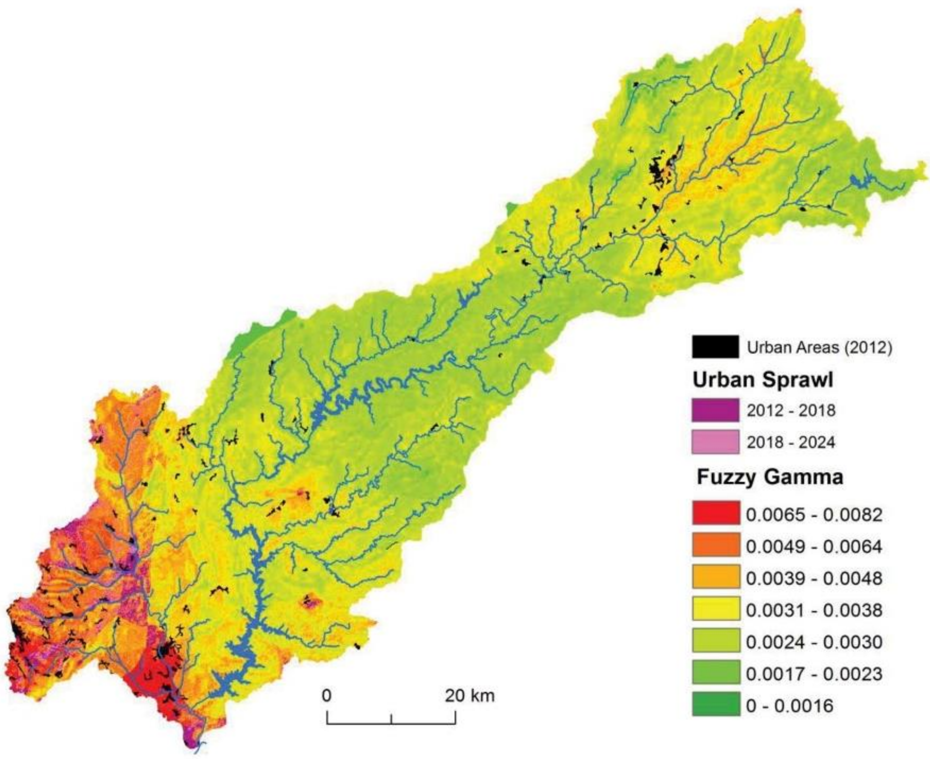

Figure 3 – Probability of urban surface in Zêzere watershed determined by Fuzzy Gamma, and the projection of urban sprawl to 2018 and 2024.

Most areas of urban sprawl identified for the two periods considered in this research have no direct implications on the quality of water of the Castelo de Bode dam, because they fall, mostly, on the Nabão Sub-basin. However, there is an increasing urban areas demand from the surrounding of the reservoirs of dams included in the Zêzere watershed, this fact, pointed out since 2002 (Vale, 1994) is also confirmed in this research, when we identify using CLC cartography for different years the appearance of new urban areas within this watershed. In the surrounding areas of the Castelo de Bode dam the highest probability of urban sprawl point out by the model is within the Vila de Rei and Cernache de Bonjardim villages areas All these human interventions in the vicinity of such a relevant drinking water reservoir might be a risk of surface water quality degradation, mainly due to insufficient sewerage system for treatment of domestic waste water, leading to the increase of certain WQP.

4.2 Risk of degradation of the water quality surface

This research point out a truly concerning tendency for an increase in the concentrations of most WQP in the Castelo de Bode dam water reservoir, with exception of NO_3^- and NO_2^- (Fig. 4).

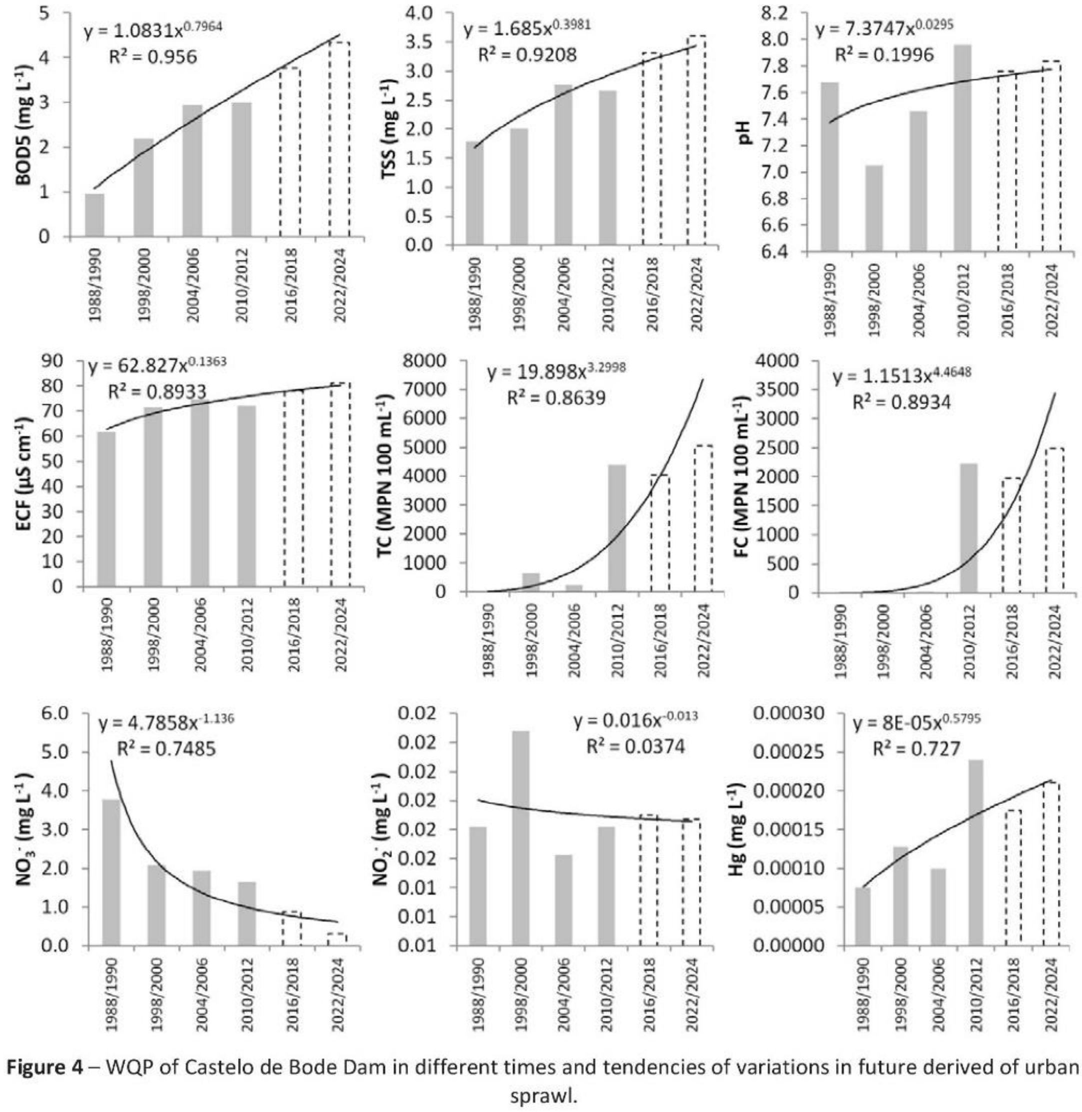

Figure 4 – WQP of Castelo de Bode Dam in different times and tendencies of variations in future derived of urban sprawl.

Analyzing in detail the variations of WQP obtained from data at stations located on this dam reservoir, we observed different variations of WQP for different periods. With the probabilities of urban sprawl and the variations of WQP, we calculated the trend of variation in the concentration of WQP to 2016-2018 periods and 2022-2024 (with the linear regression).

The BDO5 always increases along the different periods, with a slowdown between 2004-2006 and 2010-2012. This is an important WQP for the definition of water quality, but the trend of urban sprawl in the Zêzere watershed may contribute to the increase of BDO5, contributing to the risk of reduction in the quality of surface water. The case of TSS also increases between the periods analyzed, except for 2010-2012, which may be related to increased surface waterproof, but also with the consequent loss of forest area due to forest fires and deforestation causing increased water erosion (Baker, 1988). The case of the ECF increase can also be related to these LUCC, demonstrating the tendency to an increase of soluble salts in the water of the dam reservoir. In the first period pH was higher, in the second it reduced but has been increasing over time, hence the tendency is to increase in the future.

The case of TC and FC is more problematic, mainly due to the sharp increase between 2010-2012, compared to previous periods. These WQP are very related to the increase of urban surfaces in this watershed. This fact was verified in previous work establishing the correspondence between increasing artificialization of the soil and increasing concentrations of certain WQP on this dam reservoir (Meneses *et al.*, 2015). The increase of these two WQP is very much related to the appearance of new urbanizations around reservoirs in the last two decades (Vale, 2002) and with the consequent loss of drainage sewer system for subsequent treatment of waste water and solid waste. In most cases this still refers to the construction of septic tanks, adding to the already existing in the vicinity of houses, very dispersed along the surrounding areas of reservoirs, in the absence of a strict pollution discharges control, thus leading to possible contamination of downstream waters. These facts contribute to an increased risk of reduction of the quality of surface water.

The variations on the concentrations of NO_3^- and NO_2^- is largely related to agricultural crops and agricultural chemicals used to increase the profitability of soils (Cordovil, 2004). However, the land use for pursuing these anthropogenic activities is increasingly sustainable, due to the creation of more sustainable agricultural measures, in particular due to restrictions that lead to the reduction of agrochemical applications that can be dragged or leached by surface water. Hence the tendency is for the levels of NO_3^- and NO_2^- concentrations to reduce over time.

In general, most WQP have a tendency to increase in the coming years (Fig. 4) due to urban sprawl. Even considering that the most likely areas of urban sprawl were identified in this research, considering the relevance of this water reservoir for drinking supply, all watershed (particular the areas upstream of Castelo de Bode dam) should be the subject to preventive measures in order to minimize the risk of water quality degradation.

5. Conclusions

The results of this research are innovative once deeply explore and establish a cause-effect relationship between urban sprawl and the reduction of water quality in the Zêzere watershed. Furthermore they allow the determination of future trends for the two processes and their relationships, allowing the adoption of mitigation measures for the risk of water quality degradation.

The monitoring and maintenance of the LUC in Zêzere watershed is essential so that the surface water maintains an acceptable quality for public supply. Preventing degradation of these waters is essential, since there is a tendency for urban sprawl on basins of the main reservoirs of Zêzere watershed. Associated with this urban areas increase, there is the risk of degradation of surface water quality, derived from the increase of certain WQP, as for example the TC and FC. The correct management of this territory, with emphasis on preventing urban sprawl in the vicinity of the reservoirs, will contribute to the improvement of water quality, assure good quality of drinking water supply for present and future generations, and contribute to reduce the risk of diseases, assuring population health.

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Post-wildfires effects on physicochemical properties of surface water: the case study of Zêzere watershed (Portugal)

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ABSTRACT

In Portugal, wildfires are frequent and sometimes catastrophic and responsible for high damages and human losses. They have been especially intense in the Center Region of Portugal, where the Zêzere watershed is located. This research presents an analysis of the temporal and spatial occurrence of these events within the watershed. It was observed that the extent of the burned areas has a high annual variation and is not directly related to the number of reported occurrences. However, considering these factors and the high incidence of these events in some delimited sectors, environmental stress is observed, especially on the surface water quality. Water quality deterioration in the main water bodies is particularly relevant within the areas where drinking water reservoirs are located. The water quality parameters (WQPs) collected by the water quality monitoring stations (WQSs) located in these sectors (data from SNIRH) were cross-referenced with the burned areas recorded annually. Variations in the physicochemical properties of the surface water were analyzed, depending on the occurrence of wildfires and their corresponding burned areas. The increase of certain WQP downstream of watercourses that intersect sub-basins with burned areas also demonstrates the straight relation between wildfires and an increasing risk for water quality.

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1. Introduction

Wildfires cause several environmental disturbances, with relevant impact on air [1] and water quality [2]. Wildfires induce water quality degradation during the first precipitation and in the consequent runoff, which transports the elements and compounds derived from burned material deposited on the soil's surface toward water bodies [3–8].

The combustion of forest material results in the emission of dioxins and ashes into the atmosphere, which are later deposited in soil, water, and vegetation. These pollutants are mostly deposited on the burned soil surface, which may reach high levels of dioxins [9].

Fire has several effects on the soil, as illustrated by Ferreira et al. [10]: direct effects due to the action of heat on organic components (mineralization of organic matter) and indirect effects due to the disappearance of ground cover and foliage protection (susceptibility of soil to erosion and changes in the hydrological regime). The authors state that these physical processes (soil erosion) are directly related to the change of soil structure and have a relevant role in the export of nutrients, thus causing impacts downstream of the burned areas.

Among the various forms of water circulation in the burned slopes, surface runoff must be highlighted [11], through the transport of soil sediments and ash deposited on the soil's surface. When the presence of matter in the form of particles in the water is very high, be it scattered or from flotation, a rise in turbidity is observed [12].

The transport of the elements present on the soil's surface occurs through the runoff water coming from precipitation in the slopes [11]. This rain water has a good capacity for transporting materials and is considered one of the major transporting nutrients, sediments, solutes, and other particles into the watercourses [6,13,14–17].

According to Smith et al. [18], the pollutants are eroded and washed into streams by overland flow moving downslope in small channels (called rills) or in the unconcentrated flow. However, the largest water quality impacts result from high magnitude events, such as localized flash floods, large floods, and debris flows [17], these events being one of the consequences of the wildfires due to an increase of runoff in the burned areas [19–22].

Landsburg and Tiedemann [12] report that the factors with greatest impact on reducing the quality of water intended for human consumption are as follows: the turbidity, the content of sediments in suspension,

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the increase of nutrients in runoff, and increased water temperature. They state that the chemical constituents that cause greater concern for watercourse susceptibility are nitrates and nitrites, but there may be additional changes by modifying other parameters, such as the pH variation, sulfate concentration, chloride, iron, and total dissolved solids, among other components.

The elevated nitrate concentrations can persist for up to 10 years after the fire [23], but the nitrate concentrations in previously burned watersheds were lower than in their unburned counterparts, a fact observed by Riggan et al. [24] in the experimental watersheds in the San Dimas Experimental Forest in the Angeles National Forest, California.

In wildfires, the high production of polycyclic aromatic hydrocarbons (PAHs) caused by the natural vegetation burning process is also important. These compounds cause major environmental concerns because they can be mutagenic, carcinogenic, and teratogenic [3,25–29]. PAHs are produced by the incomplete combustion of organic matter [30]. These chemical compounds are emitted during wildfire activity, both in the form of gases and particles, and vary with the type of fire and combustion process. The formation of these compounds is maximized at combustion temperatures between 500 and 800°C [9].

Wildfires are responsible for major land cover changes (LUCCs) in Portugal, due to highest fire incidence in some regions, especially the Center and North of the country [31]. In mainland Portugal, the Mediterranean climate instigates the occurrence of wildfires, as the country has a spring rainy season favorable for vegetation development, followed by a very warm period favorable for triggering and developing fires [32].

Thus, the wildfires in Portugal are considered a phenomenon of the greatest environmental impact, contributing to an increase of the hydrological and erosion processes [33] and their implications on water quality. These implications are the result of the connectivity between the processes that occur in the slopes with burned areas and watercourses [10].

In Portugal, wildfires are responsible for several environmental problems, namely concerning watercourses pollution [34,35]. For example, Meneses and Cortez [8] assessed the effect of a wildfire on the physicochemical properties of the water of São Domingos stream (Western Region of Portugal) and noted an increase in the concentration of certain elements downstream of the burned area (e.g. Ca and Mg), which is higher after the first rains that generate runoff.

This research begins with the description of certain implications of wildfires on water quality and the high incidence of these events in some areas of the Portuguese territory, as the understanding of these consequences along watersheds, namely within important reservoirs integrating the drinking water supply, is a very relevant issue. Therefore, the main goal of this research is to analyze the temporal and spatial occurrence of wildfires in the Zêzere watershed to identify the effects of these events on the physicochemical properties of the surface water and the consequent implications on the water quality.

2. Materials and methods

2.1. Study area

The selected study area is the Zêzere watershed (covering 5063.9 km^2), located in the Center Region of mainland Portugal (Figure 1). This watershed is very relevant to the country because it contains an important public reservoir for the drinking water supply (Castelo de Bode Dam), responsible for the supply of most of the Lisbon metropolitan area (approximately 29% of the Portuguese population in 2015; source: Pordata).

Upstream of the watershed is the Estrela Mountain (Serra da Estrela), with a maximum altitude of 1993 m. Downstream of the watershed, the altitude decreases, and hillsides come with smaller slopes.

The relief, latitude, and continentality factors condition the spatial distribution of the rainfall in mainland Portugal. The rainfall regime is also characterized by a high spatial and interseasonal variability [36]. The rainfall changes along the study area, with the highest values in the upstream areas (Figure 2), reflect the interference of relief and elevation. The rainfall data (available at the National System of Hydrological Resources [SNIRH], Portugal) of the meteorological stations (MS) selected by each sector delimited on the watershed (Figure 1) show this spatial variation.

However, the spatial rainfall variation in the downstream areas is smaller, and the correlation between the monthly rainfall is higher (e.g. MS Constância, Castelo de Bode, and Tomar) (Figure 3). The St. Luzia (sector B, Figure 1) has no MS.

The most relevant LUCCs in the watershed, according to the Corine Land Cover of 2012 (source: European Environment Agency [EEA]), are the coverage by scrub and/or herbaceous vegetation associations (40.5%), followed by forests (29.9%) and heterogeneous agricultural areas (17.3%). The remaining area is occupied by permanent crops, arable land, open spaces with little or no vegetation, settlements, water bodies, and pastures (4, 3.5, 1.9, 1.7, 1.0 and 0.2%, respectively). However, the LUCCs of this watershed has undergone major changes in recent years, especially in the

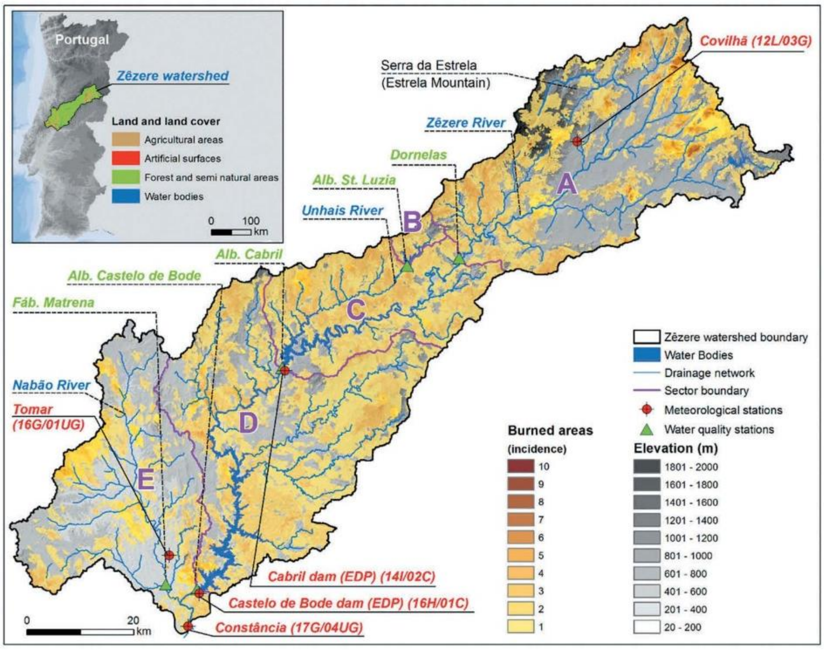

Figure 1. Zêzere watershed location and wildfires incidence.

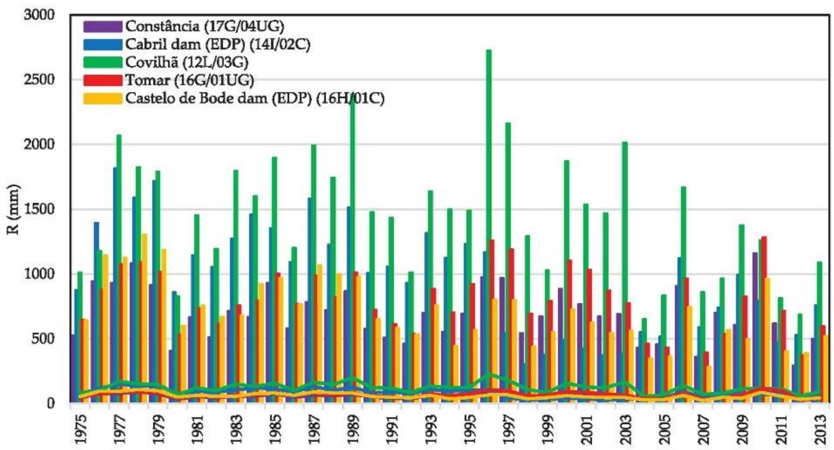

Figure 2. Total annual rainfall (R) of the selected meteorological stations and annual R average (lines).

conversion and loss of forest [37], induced mainly by the frequent wildfires that occurred over these years (Figure 1).

To evaluate the post-wildfires' effects on the surface water's physicochemical properties, the watershed was split into five sectors (Figure 1), according to the WQSs, with the available data (SNIRH). Sector A comprises the area upstream of Dornelas WQS (163,092.6 ha); sector B comprises the area drained for the St. Luzia Dam (4937.5 ha); sector C comprises the intermediate area of the watershed and integrates the Cabril Dam (73,595.9 ha); sector D comprises the reservoir of Castelo de Bode and the surrounding areas (154,819.4 ha); and sector E comprises the sub-basin of the Nabão River (109,940.7 ha), where the Fábrica da Matrena WQS is located.

2.2. *Wildfires and water quality data*

The data of the burned areas and occurrences were obtained on the Institute for Nature Conservation and

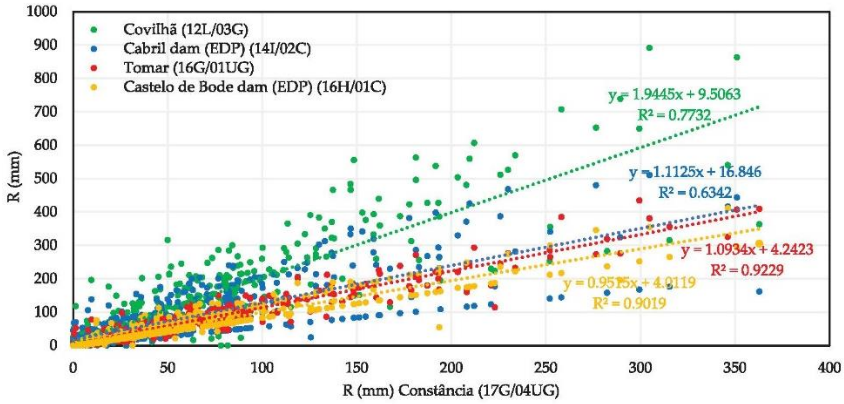

Figure 3. Relation between monthly rainfall (R) (1975–2013) of the selected meteorological stations (MS) to first downstream MS located in Zêzere watershed (Constância 17G/04UG).

Forestry (ICNF) website for mainland Portugal (vector data) for the period of 1975–2013. The Zêzere watershed boundaries (vector data) and the hydrologic data were obtained from the SNIRH database (public available data).

Since most of the WQSs in this watershed have no available data in the collection of water quality data, only the WQSs with data were chosen. Thus, there were some water quality parameters (WQPs) for which estimation was necessary due to missing data, in particular from 2011, using a linear regression with data from the closest WQS. The WQSs selected are located downstream of each delimited sector. The St. Luzia, Cabril, and Castelo de Bode WQSs are located in dam reservoirs, while the Fábrica da Matrena and Dornelas WQSs are located in main rivers (Nabão and Zêzere, respectively).

The selected WQPs (1993–2013) at these stations are as follows: pH (an important operational WQPs [38]), 5-day biochemical oxygen demand (BOD5), electric conductivity in the field (20°C) (EC), total suspended solids (TSS), total nitrate (NO_3^-), and total nitrite (NO_2^-). The PAH data are only available for 1990–1993 and 1999–2004 in the Castelo de Bode Dam WQS. Given the relevance of these WQPs to the wildfires' effects analysis on surface water's physico-chemical properties, the available data were used for the identification of possible water quality implications.

2.3. Spatial and statistical analyses

The ArcGIS 10.3 software was used for the spatial analysis of wildfires and to determine the incidence of these events. For the assessment of incidence, each annual event (single layers) has been assigned a value: "1" in case of a burned area and "0" for an unburned area. All the wildfire features were combined using a union operation, resulting in a new feature dataset, where the number of occurrences for the 1993–2013 period can be calculated for each line (polygon in the map) in the attribute table.

The fire frequency was evaluated in several studies using the Weibull function [39–43]. This procedure was also used in this work to analyze the incidence interval of wildfires (burned areas and occurrences), with the data series from the previously defined 1975–2013 interval, and to evaluate the probability of the determined number of occurrences (P_O) and burned area (P_B) to be exceeded. These probabilities were used to calculate the return periods:

$$P_O = 100 * (1 - (r_O/(N_O+1))) \quad (1)$$

$$P_B = 100 * (1 - (r_B/(N_B+1))) \quad (2)$$

Here, r_O and r_B are the order number of occurrences and the burned area, respectively; N_O and N_B are the total records of occurrences and the burned area, respectively.

However, only the period of 1993–2003 integrated the analyses performed with the WQPs (data available for the period).

For the sectors (Ss) delimited in the Zêzere watershed, the burned area was calculated, and combined statistical analyses (descriptive and analytical) were performed using the water quality's physical and chemical indicators.

In each sector, the burned areas were split as a function of the distance to the main watercourses, obtaining variables for each year (between 1993 and 2013) and the total burned area for multiple distances (ring buffers: 22, 4, 6, 8, 10, and 12 km). The distance (along the watercourses) to the burned area (≥ 1 ha) closest to each sector's WQS was also determined for each year.

To identify the wildfires' effects on the physico-chemical properties of the surface water, the software Statistica 7 was used. First, the correlation between the burned areas and rainfall in the sectors with the WQP variations (maximum values) was determined; later, the Principal Components and Classification (PCA) were used to analyze the distribution of the variables (WQPs and burned areas) from all sectors, to determine whether there are implications on the water quality between the burned areas observed by each sector, and if they are higher in sectors located downstream. All data were previously standardized.

The total burned area, annual rainfall, minimum distance between burned area (minimum 1 ha), and the total burned area in different buffers (2, 4, 6, 8, 10, and 12 km obtained with Geographic Information System––GIS) of the main watercourses were correlated with the maximum annual WQPs values.

3. Analysis of results

3.1. Wildfires in the Zêzere watershed

In the early 1990, the forest of this watershed was composed mainly of conifers (Corine Land Cover, 1990), hence the easy spread of wildfires and their difficult extinction (also due to uneven relief), resulting in large expanses of burned areas [44].

Currently, this watershed's forest is composed mainly of scrub and/or herbaceous vegetation associations, pastures, and other tree species [45], the result of wildfires and the burned areas' extension (Figure 1, with special emphasis on the 2003–2007 subperiod, Figure 4(a)) but also of the incidence of these events (Figure 1), which do not allow the forest, particularly resinous trees, to regenerate.

According to the burned area data and the occurrence of wildfires in the Zêzere watershed, we can conclude that these events are recurrent in this territory and can be regarded as one of the main events in the LUCCs that occurred here. However, the total number of occurrences has no direct relationship with the total burned area registered in this watershed. This is in line with the straight relation between wildfires and the existence of combustible material. In recent years, there have been more fires, but the burned area is smaller compared to that of previous years (Figure 4(a)). The year 2003 was notable, considering the high burned area and large burned areas near the water bodies (Castelo de Bode and Cabril Dams) (Figure 4(b)). The incidence of wildfires is also a common phenomenon in the watershed, especially in its upstream sector (Figure 1).

One of the most relevant reservoirs of drinking water in mainland Portugal, the Castelo de Bode Dam, is located within this watershed. The LUCCs from wildfires can affect the quality of surface water, due to the constant loss of vegetation cover, which results in the drag of certain chemical and physical elements from the burned soil surface through runoff, increasing their concentrations in downstream waters [8,37]. It also leads to a lower water infiltration capacity of the soil and water retention over the watershed.

The analysis of the incidence interval of wildfires shows that the Zêzere watershed had a gradual increase to approximately 100 occurrences in a return period of four years. At this point, a natural break occurs to higher return periods and larger number of occurrences (Figure 5(a)). However, the probability of the determined number occurrences being exceeded is quite high for short periods. The number of

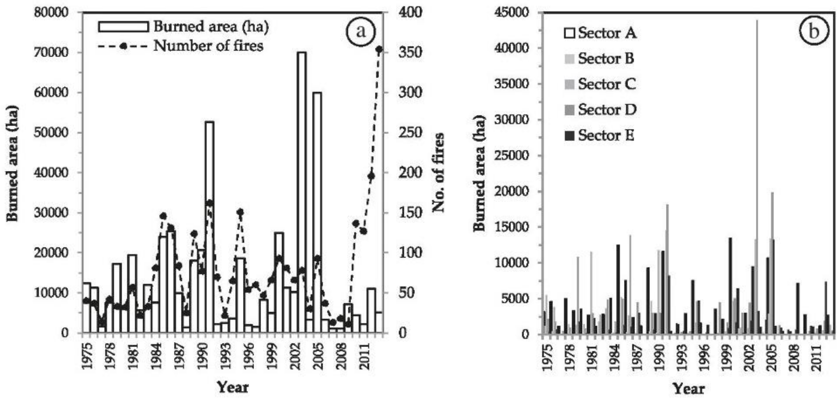

Figure 4. Burned area and number of wildfires (1975–2013) in Zêzere watershed (a) and burned area by sectors delimited in Zêzere watershed (b). Data source: ICNF.

occurrences is important in this type of research because, if many wildfires surrounding water bodies occur annually, even though each may have a reduced burned area, the sum of the burned area of the total wildfires can be high.

In the analysis of the burned area return interval (Figure 5(b)), the more extensively burned areas beyond the 15 years stand out. This analysis highlights the likelihood of wildfire occurrence in small areas with short return intervals, but illustrates that the occurrence of these devastating events, by the extent of the burned area, has a longer return period, a favorable factor for the regeneration of natural vegetation. On the other hand, the higher the plant productivity (biomass), the greater the accumulation of forest fuel, with the associated increase of wildfire consequences, depending on the severity and intensity of these events [46].

3.2. Variation of the physicochemical properties of the surface water

The selected WQPs varied differently in the sectors defined in the Zêzere watershed, but they also show many irregularities in the period under analysis (Figure 6).

In the case of the BOD5, the Fábrica da Matrena WQS presents the highest values, especially in 1994, 1999, 2002, and 2008. In the sector where this WQS is located (E), there are many industrial activities and media reports about illegal discharges in the Nabão River. Thus, the presented values may reflect these activities, which contributed in some ways to the reduction of the surface water quality in this river. However, it was found that, in 1999, there were many wildfires in this sector, which resulted in an extended burned area. These events could also partially contribute to the increase of the BOD5 registered in the Nabão River. The remaining WQSs' registered values indicate concentrations lower than 10 mg L^{-1}.

The EC also stands out in sector E (Fábrica da Matrena WQS), but this WQP has the highest registered values in sector A (Dornelas WQS) for the considered time series, especially for 2000 and 2005. The latter year also presents a considerable burned area in sector A, which can be reflected in the variation of this WQP in this sector.

The concentrations of NO_3^- and NO_2^- are also very fickle in the considered period, especially the former WQP in sector E in 2000 and the latter WQP in sector B in 1997.

The pH parameter presents, in general, the maximum values in the Castelo de Bode Dam, with a highlight on 1993. The water from this dam comes from the waters drained from sectors A, B, and C and the respective area of sector D. Thus, assessing the implications of burned areas on the physicochemical properties of the surface water exclusively in this sector is complex. This WQP is also highlighted in the St. Luzia WQS (sector B), with the maximum values observed in several years.

The high concentration of TSS stands out in the upstream sector (A) of the Zêzere River water in 2009, coinciding with the high burned area in this sector that year. Regarding the burned areas recorded in this sector, the relevant years (2000, 2001, 2003, and 2005) also reflect the maximum values of TSS recorded in this sector, demonstrating the interference of water drained from the burned areas in the increase of solid load matter in the water of this river.

In the Castelo de Bode reservoir, a high increase in the concentration of PAH was also observed in 2003 (Figure 7), coinciding with the high burned area recorded that year. The increase of this concentration

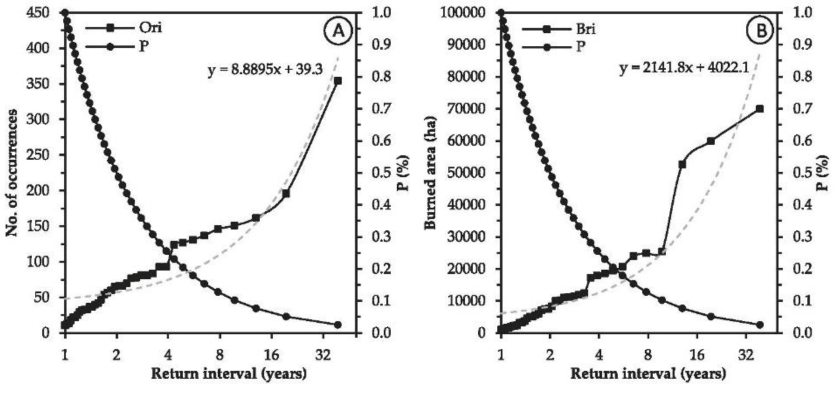

Figure 5. Wildfires (occurrences) return interval (Ori) and the probability of the determined number of occurrences to be exceeded (P) in the Zêzere watershed (Graph A). Burned area return interval (Bri) and the probability of the determined burned area to be exceeded (P) in the Zêzere watershed (Graph B). Linear trends of occurrences and burned area are represented using a dashed line.

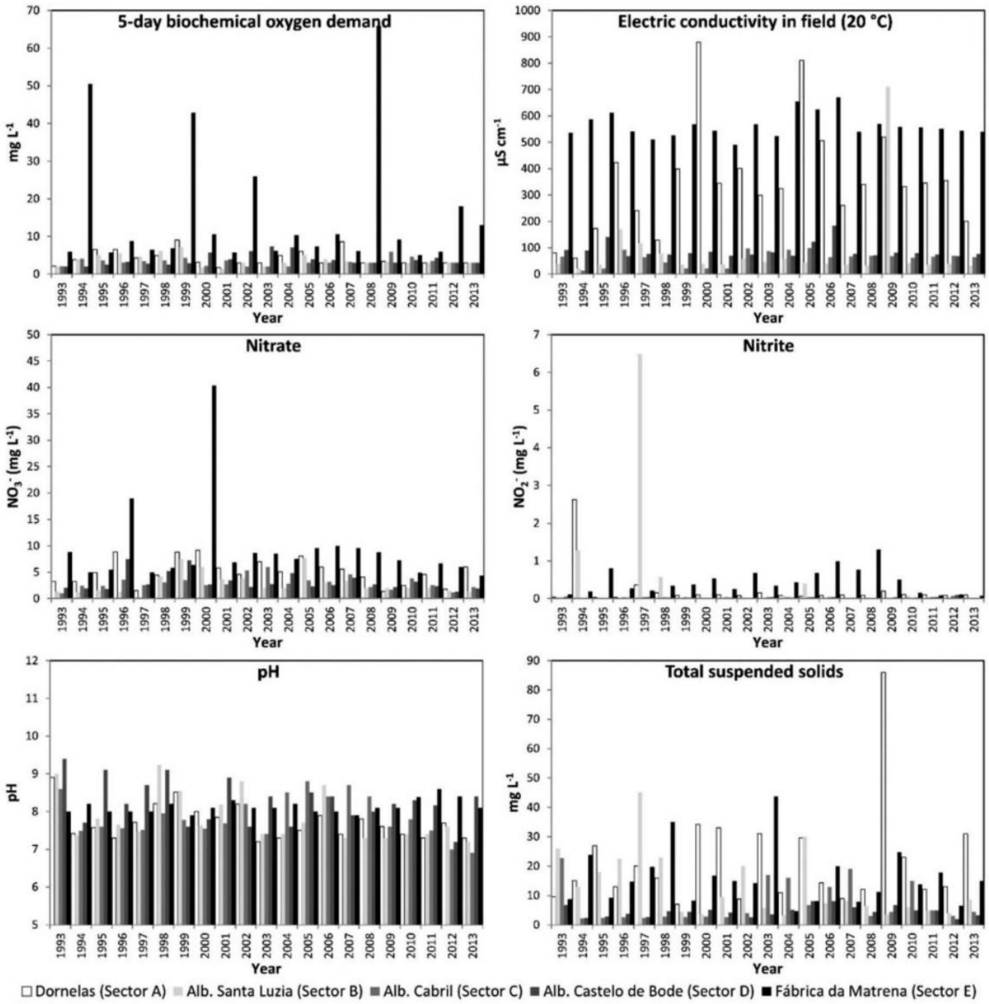

Figure 6. Maximum annual value of WQP for the surface water quality stations selected within the Zêzere watershed.

reflects the dragging of PAH by runoff that occurred in the burned areas upstream of this reservoir. In 1999, many illegal discharges (domestic and industrial effluents) into the urban sewage network or water lines were identified, which, together with the near absence of urban wastewater treatment systems, led to the discharge of high pollutant loads into the Zêzere River [47]. This fact can explain the PAH fluctuation verified in this year.

3.3. Interference of wildfires on the physicochemical properties of the surface water

The average annual WQPs and the annual burned areas for the five sectors were compared, but the results did not reveal any consistent relation. As a consequence, it was decided to cross the maximum annual WQPs value and the annual burned areas, since the availability of certain chemical compounds or elements in the burned areas is higher after wildfires, and these are easily dragged by the first rains capable of generating runoff [2,8], considering that input of these compounds or elements is identifiable in the analysis of the maximum WQPs annual value in the Zêzere watershed's surface waters. However, the relationship between the WQPs (maximum values) and burned areas in each sector is not always evident. In some cases, negative correlations were also found. The positive correlations between the burned areas with some WQPs are worthy of being highlighted: the EC and TSS in sector A, NO_3^- in Albufeira de St. Luzia (sector B)

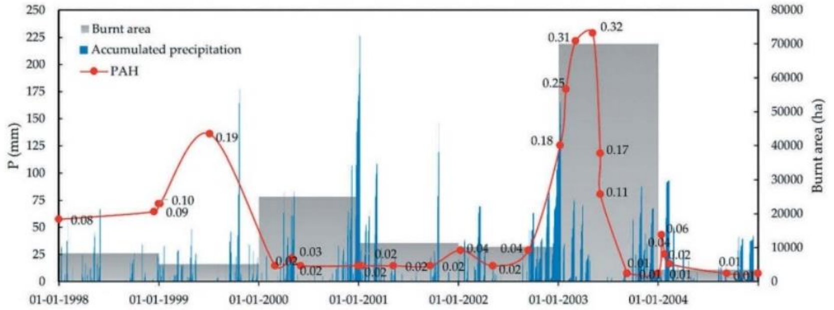

Figure 7. Variation of contents of polycyclic aromatic hydrocarbons--PAH (μg L^{-1}) in the Castelo de Bode dam reservoir and burned area (1998–2004).

and Cabril (sector C), the BOD5 in Castelo de Bode (sector D), and the EC in sector E (low positive correlation) (see Table 1).

It should also be noted that, in some cases, the burned area near the watercourses is important for certain WQP concentrations in the surface water, with this influence reducing with the increasing distance of the buffer around these watercourses (Table 1), for example, the EC in sectors A and E, and the NO_3^- in sector B. On the other hand, for the WQSs in sectors C and D, some WQP correlations tend to increase when considering the burned area of wider buffers, for example, the NO_3^- and BOD5, respectively.

In the case of the MDBA variable (minimum distance between burned area, with minimum 1 ha) and WQS, the interest lies on the negative correlations because the higher concentration of determined WQPs can be related with the reduced distance to the burned areas. However, the results do not have very strong relations with the proximity of the burned areas.

The rainfall presents very low correlations with WQPs, and in some cases, they are even negative. Positive correlations for these variables only occur in sectors D (pH) and E (NO_3^-).

The water runoff generated in the burned areas and the consecutive drag of compounds or chemical elements resulting from the wildfires to the rivers or reservoirs may not be reflected in the reference point (localization of the WQS) of each sector but may contribute to the detected increased concentration of these elements in the downstream sectors.

The Castelo de Bode Dam contains drained water from sectors A, B, C, and D. In this dam, the influence of the upstream sectors' drained waters on the increase of some WQPs was verified; hence, some established correlations between WQPs and the total burned area of these sectors also increased (Table 2).

In an advanced PCA factor analysis, the results allow the identification of groups of variables (Figure 8) that demonstrate the interference of wildfires on the physicochemical properties of the surface water. First, an interconnection or continuity is observed between sectors A, C, and D (see Figure 1) in the burned areas (main watercourse--Zêzere River), forming groups with some WQPs of these sectors (G1 and G2 in Figure 8).

For example, the TSS in Dornelas (sector A) and Cabril (sector C) integrate this grouping and demonstrate the interference of water runoff from these sectors on the increase of the solid load in the Zêzere River waters, highlighting the increased soil erosion by water as a function of the burned areas, involving the dragging of sediments by waters that run superficially downstream. The TSS in Castelo de Bode (sector D) stands out in this analysis as a function of the burned areas of St. Luzia (sector B), hence the proximity between the TSS observed in this sector (D) and the burned areas of St. Luzia.

In the projection of the variables (Figure 8), the EC observed in Cabril is also strongly connected to the burned areas recorded in this sector (C) and the upstream sector (A). This result indicates that the more burned area, the greater the concentration of dissolved minerals in the surface water within these sectors.

The variation of concentration of the WQPs NO_3^- and NO_2^- observed in each sector has no direct relationship with the burned areas, except for NO_3^- in sectors A, B, and C. In most years, the concentration of these WQPs in the upstream sectors (A and B) is higher compared with the downstream sectors (particularly in sector D). This may be due to the dilution effect on reservoirs that these sectors comprise. However, an elevated NO_3^- concentration in Castelo de Bode was punctually found, which may be the result of the concentration of waters from the upstream

Table 1. Pearson's correlation coefficients (*r*) between maximum annual value of WQP and annual burned area (1993–2013) of the sectors delimited in Zêzere watershed (significance level $p < 0.05$).

	Variable	BOD5	EC (20°C)	NO_3^-	NO_2^-	pH	TSS
Sector A	TBA	−0.089	0.588	0.404	−0.054	−0.073	0.581
	R	−0.112	0.014	0.199	0.083	0.056	0.122
	MDBA	0.308	−0.186	0.137	0.278	−0.235	−0.008
	BABW 2km	−0.065	**0.606**	0.448	−0.071	−0.112	**0.542**
	BABW 4km	−0.091	**0.574**	0.395	−0.060	−0.101	**0.601**
	BABW 6km	−0.093	**0.587**	0.398	−0.071	−0.075	**0.602**
	BABW 8km	−0.089	**0.592**	0.407	−0.074	−0.073	**0.586**
	BABW 10km	−0.087	**0.594**	0.408	−0.076	−0.070	**0.583**
	BABW 12km	−0.088	**0.594**	0.408	−0.076	−0.069	**0.582**
Sector B	TBA	0.115	−0.085	0.570	0.006	−0.015	0.335
	MDBA	−0.178	−0.178	−0.079	0.111	−0.157	−0.082
	BABW 2km	0.214	−0.069	**0.588**	−0.008	−0.035	0.340
	BABW 4km	0.181	−0.074	**0.574**	0.024	−0.035	0.360
	BABW 6km	0.140	−0.082	**0.572**	0.013	−0.024	0.345
	BABW 8km	0.115	−0.085	**0.570**	0.006	−0.015	0.335
	BABW 10km	0.115	−0.085	**0.570**	0.006	−0.015	0.335
	BABW 12km	0.115	−0.085	**0.570**	0.006	−0.015	0.335
Sector C	TBA	−0.328	0.291	0.438	0.168	0.081	0.158
	R	0.180	−0.092	−0.424	−0.268	0.051	0.172
	MDBA	0.150	0.180	0.189	−0.333	0.139	−0.033
	BABW 2km	−0.306	0.284	0.402	0.173	0.114	0.101
	BABW 4km	−0.311	0.297	0.414	0.174	0.105	0.125
	BABW 6km	−0.325	0.294	0.432	0.169	0.088	0.152
	BABW 8km	−0.328	0.291	0.438	0.168	0.081	0.158
	BABW 10km	−0.328	0.291	0.438	0.168	0.081	0.158
	BABW 12km	−0.328	0.291	0.438	0.168	0.081	0.158
Sector D	TBA	**0.532**	0.110	−0.113	0.092	0.120	0.017
	R	−0.087	0.142	0.093	−0.090	0.340	−0.003
	MDBA	−0.253	−0.193	0.174	−0.032	0.320	−0.114
	BABW 2km	**0.509**	0.133	−0.131	0.120	0.100	0.060
	BABW 4km	**0.522**	0.119	−0.115	0.106	0.115	0.040
	BABW 6km	**0.527**	0.114	−0.112	0.098	0.121	0.025
	BABW 8km	**0.532**	0.112	−0.113	0.093	0.120	0.020
	BABW 10km	**0.533**	0.111	−0.112	0.093	0.119	0.018
	BABW 12km	**0.533**	0.111	−0.112	0.093	0.119	0.018
Sector E	TBA	−0.133	0.343	−0.006	0.151	−0.050	−0.266
	R	−0.264	−0.255	0.302	−0.191	−0.046	0.209
	MDBA	−0.278	−0.262	−0.033	−0.309	−0.018	−0.301
	BABW 2km	−0.182	0.127	−0.111	0.192	−0.168	0.175
	BABW 4km	−0.135	0.385	0.067	0.246	−0.115	−0.157
	BABW 6km	−0.135	0.383	0.028	0.193	−0.086	−0.216
	BABW 8km	−0.132	0.356	0.009	0.161	−0.052	−0.245
	BABW 10km	−0.130	0.347	−0.001	0.155	−0.043	−0.259
	BABW 12km	−0.131	0.345	−0.002	0.158	−0.048	−0.264

TBA, total burned area; R, annual rainfall; MDBA, minimum distance between burned area (minimum 1 ha) and WQS; BABW, total burned area in different buffers of main watercourses.

Table 2. Pearson's correlation coefficients (*r*) between maximum annual value of WQP of Castelo de Bode WQS (sector D) and the total annual burned area (upstream sectors A, B and C, including the sector D) (significance level $p < 0.05$).

WQP	Burned area of the sectors (A + B + C + D)
BDO5	**0.52**
EC (20°C)	0.16
NO_3^-	−0.16
NO_2^-	0.03
pH	0.14
TSS	0.10

sectors and the runoff water to the sector where this reservoir is located.

The analysis of the projection of the variables shows that the pH values recorded in Cabril are related with the proximity of its the burned areas. The wildfires that occurred in this sector (B) and the vast extension of burned area (mainly from 2003 to 2005) had interference on the variation of this WQP in the downstream (Cabril reservoir).

Other evidence of the post-wildfires' effects on the physicochemical properties of the surface waters is the case of Castelo de Bode, with the BDO5 very close to the variable of this sector's burned areas (Figure 8).

4. Discussion

The study area presents a marked contrast between the upstream and downstream sectors, in particular, the slope of hillsides, the type of land use, and land cover and the spatial distribution of environmental factors (rainfall, humidity, and wind exposition, among

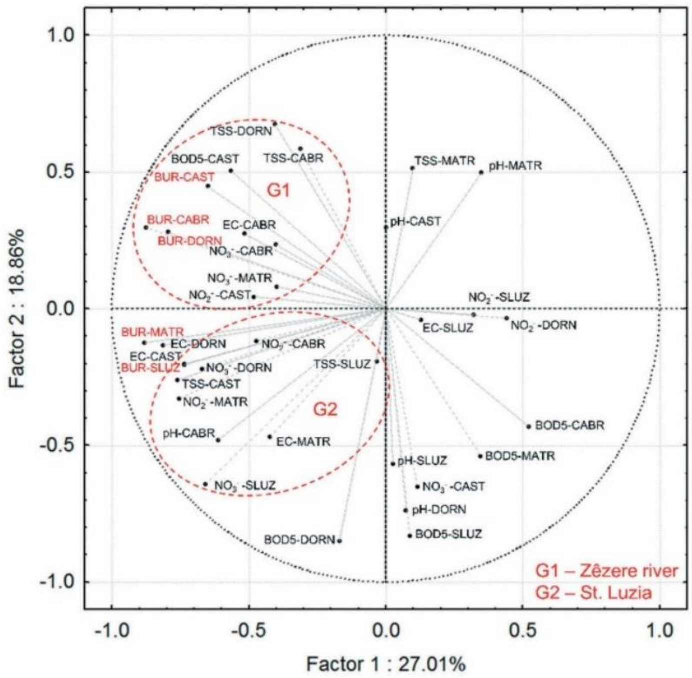

Figure 8. Projection of the variables (maximum annual value of WQP and burned area of each sector) on the factor-plane. BUR, burned area. BOD5, 5-day biochemical oxygen demand; EC, electric conductivity in field (20°C); NO_3^-, nitrate; NO_2^-, nitrite; pH; TSS, total suspended solids. Places: DORN, Dornelas (sector A); SLUZ, Alb. St. Luzia (sector B); CABR, Alb. Cabril (sector C); CAST, Alb. Castelo de Bode (sector D); MATR, Fábrica da Matrena (sector E).

others). The upstream and downstream sectors can also be differentiated according to the area affected by wildfires, which varies along the watershed, and where the previously mentioned factors also have implications on the extent of the burned areas.

The processes that occurred post-wildfires affect the water quality, especially due to the input of certain elements or substances through runoff from the burned areas. However, these effects can vary depending on the different characteristics of the fire and the environmental factors specific to the conditions of the place where these occurred (slope of hillsides, land cover, precipitation, and temperature, among the more relevant). This happens because the intensity, severity, and processes or treatments during and after a fire can have implications on the water quality [48], according to the various abovementioned processes that interconnect the hillsides with burned areas and watercourses.

In this research, an immediate increase of the concentration of NO_3^- and NO_2^- was not observed after the occurrence of wildfires in the monitored areas. These results may reflect the reduced drag of these chemical constituents from the burned areas to the water bodies but also the dilution effect caused by the water stored in reservoirs, a fact also observed in other research performed in on the São Domingos stream (located in the Western Region of Portugal) [2].

Sector E of the Zêzere watershed does not really reflect the correlation of wildfires with the variation of WQPs. Surface water in this sector is drained in its area of influence. This sector has a strong influence from anthropogenic activities (agriculture, artificialization of the soil with industrial areas, homes, roads, or similar land uses) with implications on the water quality [37,45]. However, the projection of the variables showed that the closer variables to the burned area in this sector are NO_2^- and NO_3^-. The projection of the variables also showed that these WQPs have greater proximity to the burned areas established in sectors A, B, C, and D, although there is no direct interference between these sectors and the waters of sector E.

The more visible effects, after removing the vegetable or organic material layers due to wildfires, are water erosion and the occurrence or amplification of floods, causing excess transport of sediments (source of diffuse pollution) and nutrients or compounds, such as NO_2^- and NO_3^-, which are subsequently deposited in the waterbodies [7,12]. However, in this research, it was found that, according to existing data, the increase in the concentration of these WQPs in surface waters after the Zêzere watershed wildfires is negligible, not requiring major concerns, but the persistence of these WQPs over several years post-wildfires must be taken into consideration [23]. The increase in concentration of these two WQPs should be a concern when wildfires occur in areas with a high nitrogen concentration [12].

The reduction of water quality occasionally occurred in this watershed after the occurrences of certain wildfires, especially those with large extensions of burned area, with a highlight on, for example, the increase of the TSS content. The increase of this WQP after the wildfires and the respective implications on the water quality, as well as the variation of other WQPs (pH, sulfate concentration, chloride, and iron, among other components), is also denoted by Landsburg et al. [12] and is partly explained by the increased water erosion that occurred in the burned areas and the respective dragging of sediments to the water bodies. This dragging also provides the increased turbidity of water bodies (caused by suspended material).

The correlation between the BDO5 and the burned areas was higher in sector D (Castelo de Bode). This sector also contains water drained from upstream sectors (where the incidence of wildfires is higher). This fact may reflect this WQP's increase in this area, but there may also be other factors at play, since some studies suggest the increase of this WQP is a function of the industrial and urban runoff [37,49], land use and land cover types existing in the aforementioned upstream sectors. However, the BDO5 concentration observed in Castelo de Bode can also reflect the TSS of the waters drained from the upstream sectors, where the TSS concentration is quite high and has a positive correlation with the burned areas recorded in these sectors, hence the proximity to enter these WQPs presented on the projection of the variables (Figure 8). According to Dolloff [50], the increase of suspended solids and dissolved organic matter (which is predominantly organic) contributes to the biological oxygen demand in the receiving waters.

In this research, it was observed that the EC presents a positive correlation with the burned areas (except St. Luzia), indicating the interference of water drained from the burned areas in the increase of this WQP. In contrast, pH has no relationship with the burned areas, or it is very low (Table 1). This parameter does not constitute a health concern at the levels found in the waters analyzed (the pH must be between ≥ 6.5 and ≤ 9 in conformity with the Portuguese Decree-Law 306/2007 of 27 August [51]), except for in Albufeira de Castelo de Bode in 2003 with a pH > 9. However, the research presented by Pereira et al. [52] for the northeast of the Iberian Peninsula demonstrated an increased concentration of EC and pH post-wildfire because, according to these authors, the mineralized nutrients contained in ash are easily leachable, increasing the EC.

Ash resulting from wildfires can form a significant component of suspended material flux within the first year after a fire [17]. The events of rainfall and wind post-wildfire acquire significant importance in the removal of ash on the hillslopes [53], and this ash can also transported to water bodies. Additionally, the wind impacts the wildfires' behaviors by supplying the fire with additional oxygen, which pushes it to move faster across the land [54]. However, there is a lack of data, as the effects derived from wind action are not studied in this research, but they can also contribute to increasing the compounds concentration verified in the water of the reservoirs analyzed because burned areas surround them.

There are other variables that can explain the variance of the analyzed WQPs in this watershed, i.e. fire intensity and permanence time may result in a variable severity of their consequences. This is the response of ecosystems to fire, but it can also be used to describe fire's effects on the soil, hydrological systems, fauna and flora, in the atmosphere, and also in society [55].

Many studies have demonstrated the increase of PAH in the water after wildfires [3,26,28,30]. The high concentration of PAH observed in Castelo de Bode in 2003 is a reflection of the direct and indirect implications of wildfires that occurred in this watershed on the water quality of this reservoir. This water is important for the public water supply, requiring prior treatment to prevent public health consequences, according to the PAH effects previously referenced.

According to Ferreira et al. [10], one of the most important consequences of fire passing through an area is the export of large amounts of nutrients, which may trigger downstream pollution problems, especially if there are dams and water catchment in proximity to the burned areas. This fact is confirmed in this research, but the different variations of the WQPs analyzed in the study area should be noted because there has not been an increase or reduction in parallel of all the WQPs in the surface waters after the occurrence of wildfires. The individual variation of verified WQPs may also reflect the interference of the stream waters of other sub-basins, where there may be a greater availability of the element in question, and thus lead to a concentration increase of these WQPs in water bodies from the point of where these watercourses intersect.

Figure 9. Barriers in burned areas (in gullies and slopes) of Gerês mountain, North of Portugal, constructed post-wildfires with materials of burned trees.

The rainfall that occurred in the watershed, although important for the runoff formation, has little relation with the variation of the WQPs analyzed. It would be interesting, in further work, to elaborate the analysis of this variable (R daily) and compare it with the variation of WQPs (also daily) after the wildfires.

It is worth highlighting that the effects of wildfires on surface water were only observed when analyzing the maximum values of the WQPs, not the annual average of each WQP. This somehow reflects the higher drag of the elements or chemical compounds resulting from the wildfires occurring in a very specific period (in particular, the first rainfall after the wildfires able to generate surface runoff) [8,56] but also the stability of ecosystems on the retention of these elements, dissipating this dragging to the water bodies over time. This happens because, on one hand, the greatest concentration of WQPs occurs during the first rains (by dragging in the water runoff and leaching), and on the other hand, because there is retention or assimilation by vegetation that grew in the burned areas [2]. In this sense, the post-wildfire precipitation can explain the degree to which wildfires degraded the water quality and supply, but this factor cannot be analyzed independently, i.e. a group of multiple factors that explain the water quality and supply variations (e.g. the extent and intensity of the wildfire, the watershed topography, and the local ecology) must be integrated [17].

Developing a system of mitigation measures is important to the water quality supply. Sham et al. [57] relates some measures, for example, properly designed forest riparian buffer strips that can protect source waters from wildfire-related runoff problems. Limiting the scope and burn intensity of wildfires can also significantly mitigate the sediment problems of these watercourses.

The magnitude of the effects on water quality increases with burn severity [57], but the reduction and maintenance of the forest materials available can minimize this severity, and this constitutes a simple measure that can be implemented by forest owners. On the other hand, if the replanting of burned areas is done using pyrophytes species, forest owners can introduce corridors of species more resistant to fire (e.g. *Quercus sp.*), thus contributing to minimizing large wildfires. The creation of barriers with forest material post-wildfire in watercourses or slopes (Figure 9) can provide the reduction of soil loss and, consequently, of the particles suspended in water.

Preventing the flow of burned areas from occurring directly into water bodies would be essential to avoid increasing the concentration of certain WQPs. In this sense, some preventive short-term post-fire measures may be drainage through artificial channels, the application of straw on the burned areas, and placement of barriers in the water lines, among others. In the long term, it may be forest management, namely avoiding reforestation with flammable species in the vicinity of water bodies. It is also important to mention that drinking-water treatment must always be adjusted in accordance with changes in source-water chemistry.

5. Conclusions

This work presents research on the distribution of wildfires (spatially and temporally) over the Zêzere watershed, in mainland Portugal, and their implications on the surface water quality. Wildfires were responsible for large LUCCs in this watershed, and the sector upstream was where there has been greater incidence of these events. Due to the high number of annual occurrences and the extension of the burned areas and their incidence, most of these events are considered catastrophic, not only because of the material damage, but also because it reduces the surface water quality. This is considered an important environmental problem because the Zêzere watershed comprises the main reservoir of drinking water in mainland Portugal (Castelo de Bode Dam).

Further, it was verified that the return period for the wildfires with reduced burned areas is very short, this type of event having a high probability of recurrence.

The statistical methods applied in this research confirm the impacts of the wildfires on the physicochemical properties and changes in the surface water. In some cases, there have been changes in the physicochemical properties of the water directly in the watercourses closest to the burned areas, while in other cases, there were changes in the water bodies located downstream of the point of monitoring (WQS). These results indicate that there is a continuity of the effects of wildfires along the watercourses but also the increase of certain WQPs after the intersection of several streams draining sub-basins within the burned areas.

The year 2003 was particularly catastrophic in this watershed, with extensive burned areas, and the effects of wildfires were very evident in the increase of the concentration of PAHs and other WQPs in the Castelo de Bode Dam. These results indicate that these events impact the surface water quality.

The results of this work are important for the management of the water bodies of the Zêzere watershed and others but also for forest management, especially in the reforestation of burned areas with fire-resistant species. This may contribute to the reduction of the incidence of these events, thus reducing possible implications of these events on the water quality.

Disclosure statement

No potential conflict of interest was reported by the authors.

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CONSIDERAÇÕES GERAIS DA TESE

A avaliação das AUOS é uma temática com elevada importância na atualidade, porque é fundamental perceber quais as implicações que estas podem trazer para o Ambiente, mas também para o Homem (socioeconómicas) e outros seres vivos.

O principal objetivo proposto nesta tese foi globalmente alcançado, i.e., a avaliação das AUOS (a diferentes escalas e temporalmente) utilizando CDG de UOS com diferentes propriedades foi realizada com sucesso, sendo possível a partir dos resultados obtidos nas diferentes modelações (efetuadas para as diferentes análises ambientais apresentadas) perceber que há efetivamente interferência nos resultados, consoante a geoinformação de UOS utilizada em cada uma.

O UOS de Portugal continental variou muito ao longo das últimas décadas, mas as AUOS observadas são bastante diferenciadas espacialmente e temporalmente quando se compara as dinâmicas das diferentes regiões que compõem este território, resultado de múltiplas forças motrizes.

As AUOS mais representativas neste território ocorreram nas áreas florestais. Este tipo de UOS apresentou elevada redução de área nas últimas décadas, por um lado devido aos incêndios florestais, por outro, devido à desflorestação. Pelo contrário, os solos artificializados aumentaram, com grande destaque nas Áreas Metropolitanas de Lisboa e Porto. Também se observaram transições nas áreas agrícolas, determinadas culturas como por exemplo as de sequeiro deram lugar às culturas de regadio, neste caso mais proeminente no Alentejo, em consequência da maior disponibilidade de água para regadio proporcionada pela construção da barragem do Alqueva.

No entanto, os resultados das AUOS são diferenciados consoante o conjunto de geoinformação de UOS que integrou cada avaliação apresentada nesta tese. Verificou-se que há discrepância de área entre algumas classes da COS relativamente às da CLC (nos primeiros 3 níveis). Embora estes conjuntos de geoinformação sejam de diferentes momentos e tenham propriedades diferentes, não apresentam uma sequência lógica de variação de área pelas diferentes classes quando se colocam as séries cartográficas ordenadas temporalmente e, quando se comparam as séries com datas muito próximas (COS *vs*. CLC), observaram-se diferenças significativas de área em termos absolutos.

Observaram-se também algumas desproporcionalidades espaciais nas AUOS calculadas entre as diferentes regiões de Portugal continental. A título exemplificativo, evidencia-se a elevada artificialização do solo na região de Lisboa, processo que não acompanha o ritmo de artificialização de outras regiões, mas neste tipo de AUOS em particular também se destaca o período de recessão económica que Portugal foi alvo na última década, sobretudo no abrandamento de infraestruturação, facto que demonstra a necessidade de se estudar em paralelo às AUOS as forças motrizes que lhes deram origem.

Algumas forças motrizes podem explicar as diferentes dinâmicas temporais das AUOS observadas, por exemplo, em determinadas regiões observou-se num determinado período o aumento de áreas de mato em consequência da perda de área agrícola, mas posteriormente observou-se a sua transição novamente para área agrícola, facto explicado inicialmente pelo abandono agrícola (crescimento da vegetação natural) e depois pelo seu retrocesso, evidenciando-se nesta situação causas essencialmente socioeconómicas (e.g. envelhecimento da população, emigração, distribuição de fundos comunitários, entre outros). Outro exemplo é a transição de pinhal ou áreas de mato para eucaliptal, facto explicado pela rentabilidade que este tipo de ocupação florestal proporciona a curto prazo, o forte investimento da indústria da celulose neste tipo de espécies, entre outros, fatores que se evidenciam no valor acrescentado bruto de algumas regiões, mas a expansão de área ocupada por este tipo de espécies florestais tem sido muito contestada no geral, sobretudo porque são espécies que têm contribuído para grandes extensões de área ardida resultante dos incêndios florestais, mas também para o agravamento da severidade destes eventos.

Em relação aos incêndios florestais, estes eventos têm dizimado a floresta das regiões Centro e Norte, com alguma expressão também nas serras algarvias, mas destaca-se a primeira região com a maior incidência e também pela grande extensão de alguns incêndios que aqui têm ocorrido nos últimos anos. Uma das conclusões apresentadas no artigo Meneses *et al.* (2018a) é o aumento de áreas ardidas de matos, sendo estas também as áreas que apresentam elevada probabilidade de ocorrer novos incêndios florestais. Contudo, esta probabilidade elevada é explicada em grande parte pela ocorrência de incêndios sobretudo em pinhal e, como a recorrência é muito elevada, não há capacidade de regeneração dos pinheiros, dando lugar aos matos (processo natural), o que explica em grande parte o aumento de área ardida de matos em anos mais recentes (reincidência nos matos).

Os incêndios florestais têm implicações ambientais, facto que se evidenciou nesta tese, nomeadamente pelas perturbações verificadas na qualidade da água superficial da bacia hidrográfica do Rio Zêzere (muito afetada por estes eventos nos últimos anos). Esta é uma das conclusões apresentada no artigo Meneses *et al.* (2019b), onde se evidenciam relações diretas entre a ocorrência de incêndios florestais e a variação de alguns parâmetros de qualidade da água, neste caso com evidente redução da qualidade da água. Porém, as perturbações causadas pelas AUOS na qualidade da água não se devem apenas a estes eventos, algumas ações antrópicas também têm contribuído para a sua degradação, nomeadamente o aumento de áreas agrícolas e o aumento de áreas artificializadas nas imediações dos corpos de água (Meneses *et al.*, 2016b), com relevo para o aumento da indústria pecuária, entre outros. Estas ações ou atividades têm contribuído para o *input* e respetivo aumento da concentração de determinados elementos químicos nos principais corpos de água (casos verificados nos principais corpos de água da bacia hidrográfica do Rio Zêzere, conforme se pode constatar na análise dos resultados apresentados no artigo Meneses *et al.*, (2015).

Alguns métodos utilizados em determinadas investigações apresentadas nesta tese podem ser utilizados em diferentes contextos. Por exemplo, o Valor Informativo foi utilizado para modelar a suscetibilidade a movimentos de vertente, um método amplamente reconhecido pela comunidade científica pelos bons resultados que apresenta nesta temática, mas a utilização deste na modelação da probabilidade de artificialização do solo também apresentou elevada eficiência.

Verificou-se que nas conversões de geoinformação de UOS de vetor para *raster* (com diferentes resoluções), ocorrem processos de generalização que fizeram variar os resultados consoante a resolução espacial escolhida (Meneses *et al.*, 2018). Resultados com elevadas resoluções são muito semelhantes aos obtidos com o vetor. No caso de modelações à escala de Portugal continental pode utilizar-se resolução de 50 m, porque, por um lado, os resultados das AUOS têm elevada correlação com os obtidos com o vetorial, mas por outro, esta resolução apresenta vantagens operacionais, quer no processamento, quer no espaço ocupados nas bases de dados.

Geoinformação de UOS mais detalhada (nomeadamente a COS) permite obter resultados mais precisos, por exemplo na determinação dos locais onde irão ocorrer os próximos movimentos de vertente, enquanto a generalização da geoinformação (implícita na CLC) vai refletir-se também na generalização dos resultados, facto verificado no artigo Meneses *et al.* (2019a). Neste artigo verificou-se que a suscetibilidade a deslizamentos de vertente se prolongou por vários segmentos da rede viária. Ambos os resultados obtidos nos dois modelos (com a COS e com a CLC) foram validados, sendo estes aceitáveis para integrar planos de ordenamento do território pelo rigor e fiabilidade que encerram. Verificou-se, através das curvas de sucesso e cálculo da área abaixo da curva, que estes modelos apresentam elevada eficiência na determinação dos locais (ao longo da rede viária) onde provavelmente irão ocorrer perturbações derivadas de movimentos de vertente.

Contudo, quando se trata de riscos naturais, deve-se procurar a maior a precisão na determinação dos locais com a maior probabilidade de ocorrer determinado evento, realçando-se desta forma a importância da utilização de geoinformação mais detalhada.

As diferentes propriedades dos conjuntos de geoinformação de UOS utilizados nas diversas investigações apresentadas podem explicar as diferenças encontradas em alguns resultados obtidos.

Cada conjunto de geoinformação de UOS deve servir os propósitos para o qual foi elaborado, i.e., a COS, sendo mais detalhada, permite análises espaciais mais pormenorizadas, propriedades que lhe conferem mais adequabilidade para a utilização em análises espaciais à escala municipal ou à microescala, enquanto a CLC, por ser mais generalizada, a sua utilização é mais adequada à macroescala, nomeadamente às escalas regional ou nacional. Contudo, ambos os conjuntos de geoinformação permitem a análise à escala regional ou nacional, por serem compatíveis na sua nomenclatura até ao 3.º nível, mas esta análise deve ser equacionada, pois certamente haverá discrepância nos resultados, facto explicado essencialmente pelas diferentes propriedades de cada conjunto de geoinformação. Além disto, pode também estar presente a incerteza nos conjuntos de geoinformação de UOS selecionados, pois como menciona Goodchild (2018), é impossível que qualquer item de geoinformação seja perfeito quanto à sua exatidão, facto que pode explicar em parte também algumas diferenças nos resultados obtidos com os dois conjuntos selecionados para as diferentes investigações apresentadas.

Na análise de problemas com representação espacial mais específicos, como é o caso dos incêndios florestais, a geoinformação de UOS nem sempre apresenta a totalidade da área afetada por estes eventos, facto que pode resultar das especificações ou critérios considerados na elaboração da cartografia em causa, ou outros fatores (e.g. cartografia elaborada por diferentes fotointérpretes, podendo variar a sensibilidade e rigor). Este é um exemplo em que a omissão de informação na representação cartográfica pode induzir os utilizadores em erro, daí a necessidade de se avaliar adequadamente as propriedades de cada conjunto de geoinformação, onde se inclui a análise dos métodos e critérios utilizados para a sua elaboração.

Um problema que não foi aprofundado nesta tese, mas que também pode ter interferência nos resultados é a utilização de diferentes *softwares* de SIG, ou mesmo diferentes ferramentas de um único *software*, que permitem obter a mesma tipologia de resultados, pois podem variar as especificações dos métodos acoplados às ferramentas em utilização. Por exemplo, são múltiplas as especificações dos métodos de conversão vetor-*raster*, nomeadamente a informação atribuída à célula pode ser: com base na informação do polígono que se sobrepõe ao centro desta célula, critério utilizado no artigo Meneses *et al.* (2018); com base na área prevalecente de um polígono quando existem vários sobrepostos sobre a mesma célula; com base na área máxima combinada dos polígonos com a mesma informação coincidentes com a mesma célula, entre outros critérios. Por norma, os utilizadores não têm a preocupação ou a sensibilidade suficiente para testar os diferentes métodos e perceber as interferências resultantes da escolha de diferentes critérios neste tipo de conversões, deixando por defeito as opções apresentadas inicialmente nas ferramentas utilizadas. Esta é uma problemática que pode ser explorada noutras investigações complementares a esta tese.

No geral, considera-se que os resultados apresentados nesta tese e a respetiva discussão são um contributo elementar para se perceber que, por um lado, é fundamental progredir na qualidade da geoinformação produzida, em particular da geoinformação temática de UOS, de forma a que esta seja mais útil à gestão do território e desenvolvimento dos países e das nações; por outro, é essencial avaliar as propriedades de geoinformação de UOS a considerar numa determinada modelação para que se perceba qual a sua interferência nos resultados.

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ANEXOS

Anexo 1. Área de transição (‰) da ocupação do solo a nível global entre 1992 e 2015.

1992 \ 2015	Área agrícola, sequeiro	Vegetação herbácea	Vegetação arbórea ou arbustiva	Área agrícola, regadiao ou em área inundada	Mosaico de área agrícola (>50%) / vegetação natural (arbórea, arbustiva, herbácea) (<50%)	Mosaico de vegetação natural (arbórea, arbustiva, herbácea) (>50%) / área agrícola (<50%)	Vegetação arbórea, folhosas, perene, fechada para aberta (>15%)	Vegetação arbórea, folhosas e de folha caduca	Vegetação arbórea, aciculifoliada, perene	Vegetação arbórea, aciculifoliada e de folha caduca	Vegetação arbórea, do tipo misto (folhosas e aciculifoliada)	Mosaico de árvores e arbustos (>50%) / vegetação herbácea (<50%)	Mosaico de vegetação herbácea (>50%) / árvores e arbustos (<50%)	Vegetação arbustiva	Pastagens	Líquens e musgos	Vegetação esparsa (arbórea, arbustiva, herbácea) (<15%)	Vegetação arbórea esparsa (<15%)	Vegetação arbustiva esparsa (<15%)	Vegetação herbácea esparsa (<15%)	Vegetação arbórea, em área alagada, água doce e salgada	Vegetação arbórea, em área alagada, água salina	Vegetação herbácea e arbustiva, em área alagada, água doce e salgada	Áreas urbanas	Solo descoberto	Corpos de água	Neves eternas e glaciares	
	10	11	12	20	30	40	50	60	70	80	90	100	110	120	130	140	150	151	152	153	160	170	180	190	200	210	220	Total
10	12,058	0,001	0,000	0,000	0,000	0,001	0,020	0,039	0,018	0,002	0,005	0,011	0,001	0,011	0,026	0,000	0,003	0,000	0,000	0,000	0,001	0,001	0,000	0,156	0,004	0,008	0,000	12,367
11	0,000	11,389	0,000	0,000	0,000	0,000	0,005	0,015	0,002	0,001	0,001	0,005	0,000	0,003	0,007	0,000	0,002	0,000	0,000	0,000	0,001	0,000	0,000	0,154	0,001	0,001	0,000	11,587
12	0,000	0,000	0,267	0,000	0,000	0,000	0,002	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,002	0,000	0,000	0,000	0,274
20	0,000	0,000	0,000	3,418	0,000	0,000	0,001	0,003	0,000	0,000	0,000	0,001	0,000	0,000	0,003	0,000	0,003	0,000	0,000	0,000	0,000	0,001	0,000	0,061	0,001	0,001	0,000	3,493
30	0,001	0,002	0,000	0,000	4,955	0,004	0,168	0,073	0,017	0,004	0,012	0,027	0,001	0,016	0,022	0,000	0,004	0,000	0,000	0,000	0,006	0,004	0,000	0,027	0,004	0,006	0,000	5,355
40	0,001	0,002	0,000	0,000	0,001	4,610	0,104	0,248	0,075	0,009	0,032	0,084	0,002	0,015	0,066	0,000	0,011	0,000	0,000	0,001	0,008	0,004	0,001	0,023	0,007	0,009	0,000	5,314
50	0,069	0,112	0,009	0,003	0,426	0,216	15,845	0,021	0,000	0,000	0,000	0,104	0,010	0,129	0,048	0,000	0,004	0,000	0,000	0,000	0,054	0,002	0,035	0,005	0,000	0,044	0,000	17,136
60	0,097	0,173	0,003	0,013	0,095	0,106	0,020	15,161	0,001	0,000	0,001	0,085	0,011	0,256	0,099	0,000	0,005	0,000	0,000	0,000	0,000	0,000	0,053	0,014	0,003	0,007	0,000	16,204
70	0,051	0,040	0,001	0,016	0,050	0,054	0,000	0,002	18,377	0,008	0,001	0,225	0,033	0,232	0,095	0,000	0,126	0,000	0,001	0,000	0,001	0,000	0,083	0,019	0,029	0,078	0,000	19,524
80	0,000	0,004	0,000	0,000	0,003	0,010	0,000	0,000	0,000	13,119	0,000	0,058	0,037	0,078	0,018	0,000	0,019	0,000	0,000	0,000	0,000	0,000	0,010	0,001	0,010	0,002	0,000	13,370
90	0,011	0,005	0,000	0,001	0,005	0,004	0,000	0,001	0,001	0,000	4,365	0,023	0,003	0,015	0,009	0,000	0,003	0,000	0,000	0,000	0,000	0,000	0,026	0,002	0,001	0,002	0,000	4,475
100	0,005	0,006	0,001	0,001	0,004	0,011	0,005	0,013	0,017	0,015	0,002	5,467	0,011	0,050	0,044	0,000	0,021	0,000	0,000	0,000	0,001	0,000	0,004	0,024	0,005	0,001	0,000	5,708
110	0,011	0,012	0,000	0,003	0,004	0,009	0,003	0,025	0,040	0,038	0,002	0,022	1,655	0,003	0,000	0,000	0,021	0,000	0,002	0,002	0,001	0,000	0,001	0,004	0,011	0,001	0,000	1,869
120	0,140	0,110	0,000	0,010	0,071	0,052	0,129	0,302	0,109	0,034	0,021	0,093	0,007	20,136	0,042	0,000	0,022	0,000	0,000	0,000	0,009	0,002	0,002	0,027	0,007	0,007	0,000	21,332
130	0,042	0,110	0,000	0,030	0,054	0,085	0,009	0,047	0,036	0,016	0,003	0,043	0,001	0,017	20,035	0,000	0,221	0,000	0,000	0,015	0,002	0,001	0,003	0,061	0,072	0,012	0,000	20,917
140	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	5,052	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	5,052
150	0,125	0,062	0,002	0,018	0,049	0,066	0,000	0,007	0,129	0,123	0,004	0,059	0,032	0,011	0,342	0,000	17,650	0,000	0,000	0,000	0,006	0,000	0,009	0,009	0,183	0,016	0,000	18,903
151	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
152	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,002	0,000	0,000	0,002	0,000	0,000	0,000	0,000	0,000	0,000	0,131	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,137
153	0,000	0,004	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,007	0,000	0,000	0,000	0,000	0,485	0,000	0,000	0,000	0,000	0,003	0,000	0,000	0,500
160	0,000	0,003	0,001	0,000	0,004	0,003	0,055	0,000	0,000	0,000	0,000	0,007	0,000	0,004	0,001	0,000	0,002	0,000	0,000	0,000	1,285	0,000	0,007	0,001	0,000	0,009	0,000	1,381
170	0,000	0,001	0,000	0,001	0,001	0,001	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,260	0,001	0,001	0,000	0,004	0,000	0,271
180	0,002	0,007	0,000	0,000	0,001	0,006	0,009	0,065	0,311	0,024	0,056	0,070	0,002	0,009	0,008	0,000	0,006	0,000	0,000	0,000	0,026	0,001	3,717	0,005	0,001	0,022	0,000	4,349
190	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,572	0,000	0,000	0,000	0,572
200	0,005	0,017	0,000	0,040	0,003	0,005	0,000	0,001	0,001	0,002	0,000	0,001	0,006	0,001	0,261	0,000	0,313	0,000	0,001	0,030	0,000	0,000	0,000	0,027	29,631	0,013	0,000	30,360
210	0,005	0,006	0,000	0,004	0,003	0,003	0,007	0,005	0,049	0,006	0,002	0,005	0,002	0,008	0,011	0,000	0,012	0,000	0,002	0,000	0,004	0,009	0,047	0,006	0,079	675,491	0,000	675,768
220	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	103,783	103,783
Total	12,623	12,064	0,287	3,559	5,730	5,245	16,383	16,030	19,186	13,403	4,508	6,395	1,817	20,994	21,143	5,052	18,447	0,000	0,139	0,533	1,407	0,284	4,000	1,201	30,052	675,735	103,783	1000
Ganhos	0,566	0,675	0,019	0,141	0,775	0,635	0,538	0,869	0,809	0,284	0,143	0,929	0,162	0,858	1,108	0,000	0,797	0,000	0,008	0,048	0,122	0,024	0,283	0,629	0,421	0,244	0,000	
Perdas	-0,309	-0,198	-0,006	-0,075	-0,400	-0,704	-1,291	-1,043	-1,147	-0,251	-0,110	-0,242	-0,214	-1,196	-0,882	0,000	-1,253	0,000	-0,005	-0,015	-0,096	-0,011	-0,632	0,000	-0,729	-0,277	0,000	

Anexo 2. Material suplementar do artigo Meneses *et al.* (2019a), publicado no Natural Hazards and Earth System Sciences Journal.

1. Tabulate area between slope and CLC 2006 (area ha).

Slope (degree)	Urban fabric (UF)	Industrial, commercial and transport units (ICT)	Mine, dump and construction sites (MDC)	Artificial, non-agricultural vegetated areas (ANA)	Arable land (AL)	Permanent crops (PC)	Pastures (P)	Heterogeneous agricultural areas (HAA)	Forests (F)	Scrub and/or herbaceous vegetation associations (SHV)	Open spaces with little or no vegetation (OSV)	Inland waters (IW)	Total
>40	1.3	0.3	2.7	0.0	1.2	1.0	0.0	22.8	243.5	428.2	321.6	7.1	1029.5
36 - 40	4.8	2.0	13.9	0.0	4.1	5.9	0.1	91.7	1106.0	1953.5	474.1	15.7	3671.9
31 - 35	16.1	4.0	25.4	0.0	14.8	25.7	1.0	370.8	4009.2	7138.7	880.7	35.5	12521.8
26 - 30	44.1	8.2	18.2	0.0	48.0	85.2	4.4	1116.8	10103.0	17846.1	1231.3	48.0	30553.5
21 - 25	108.7	18.4	19.2	0.1	103.4	254.8	10.7	2697.9	18531.3	32096.1	1499.4	56.2	55396.1
16 - 20	231.8	43.9	25.3	1.9	192.1	721.4	12.6	5565.6	25873.6	42954.9	1775.8	63.3	77462.3
11 - 15	558.7	102.6	51.3	10.1	417.0	2033.3	35.2	11979.7	28887.2	44681.1	1982.6	69.7	90808.4
6 - 10	1511.5	292.3	150.2	17.5	2017.1	4734.0	78.4	24733.2	22169.8	34541.3	1955.0	83.1	92283.5
0 - 5	3563.6	884.3	168.8	36.1	14479.9	10464.5	250.9	45561.6	25241.2	35734.5	1573.2	4714.4	142672.9

2. Tabulate area between slope and COS 2007 (area ha).

Slope (degree)	Urban fabric (UF)	Industrial, commercial and transport units (ICT)	Mine, dump and construction sites (MDC)	Artificial, non-agricultural vegetated areas (ANA)	Arable land (AL)	Permanent crops (PC)	Pastures (P)	Heterogeneous agricultural areas (HAA)	Forests (F)	Scrub and/or herbaceous vegetation associations (SHV)	Open spaces with little or no vegetation (OSV)	Inland waters (IW)	Total
>40	0.4	1.7	3.2	0.1	0.8	3.1	0.6	5.6	263.7	475.7	271.8	2.8	1029.5
36 - 40	2.9	3.0	12.8	0.3	1.6	14.1	0.2	37.3	1186.2	2072.1	339.3	2.1	3671.9
31 - 35	16.8	10.8	23.5	0.5	7.3	66.4	1.2	161.5	4416.1	7220.2	592.3	5.5	12521.8
26 - 30	72.3	29.5	18.7	1.3	26.7	215.8	6.6	499.0	11587.2	17279.8	803.8	12.8	30553.5
21 - 25	228.0	64.2	28.7	3.4	81.6	590.6	24.2	1289.4	22081.1	29960.1	1018.3	26.6	55396.1
16 - 20	640.3	126.3	67.3	11.8	247.9	1388.4	74.5	2765.9	31771.4	39040.6	1278.1	49.9	77462.3
11 - 15	1746.5	284.4	176.9	27.3	832.5	3513.6	333.2	5727.7	36498.2	40024.9	1554.0	89.2	90808.4
6 - 10	4035.5	719.3	382.9	68.8	3819.1	8009.9	1399.2	10665.3	29664.0	31895.7	1486.6	137.1	92283.5
0 - 5	7506.4	1845.0	500.6	195.3	19700.3	15814.5	4316.4	17961.7	34878.8	32410.4	1162.5	6381.1	142672.9

3. Conditional and priori probabilities (CP and PP, respectively) of landslides occurrence in Zêzere watershed.

PFM	Classes	Watershed area (%)	Landslides test area (%)	CP	PP	IV*
Slope angle	0 - 5	28.17	1.69	0.000098	0.001652844	-2.824
	06-Oct	18.22	2.07	0.000205887	0.001652844	-2.083
	Nov-15	17.93	5.73	0.000616683	0.001652844	-0.986
	16 - 20	15.30	12.97	0.001432955	0.001652844	-0.143
	21 - 25	10.94	17.48	0.002798032	0.001652844	0.526
	26 - 30	6.03	17.95	0.005498557	0.001652844	1.202
	31 - 35	2.47	17.76	0.011180483	0.001652844	1.912
	36- 40	0.73	10.71	0.020153219	0.001652844	2.501
	41- 45	0.16	10.90	0.090941242	0.001652844	4.008
	46 - 50	0.03	2.54	0.159235669	0.001652844	4.568
	51 -55	0.01	0.19	0.042390844	0.001652844	3.244
	> 55	0.01	0	0	0.001652844	**-2.824**
Slope Curvat.	Convex	32.60	61.05	0.003095092	0.001652844	0.627
	Straight	28.25	4.90	0.000286567	0.001652844	-1.752
	Concave	39.14	34.05	0.001437748	0.001652844	-0.139
Aspect	Plane	13.58	0	0	0.001652844	**-0.570**
	N	8.45	4.78	0.000934889	0.001652844	-0.570
	NE	9.61	9.80	0.001684777	0.001652844	0.019
	E	10.85	7.41	0.001128231	0.001652844	-0.382
	SE	12.29	12.78	0.001719648	0.001652844	0.040
	S	11.49	8.36	0.001203415	0.001652844	-0.317
	SW	12.26	13.74	0.001852416	0.001652844	0.114
	W	11.22	24.97	0.003676985	0.001652844	0.800
	NW	10.25	18.16	0.002927674	0.001652844	0.572
Slope over area ratio	5 - 7.5	3.04	13.02	0.007077835	0.001652844	1.454
	7.6 - 10	57.75	55.79	0.001596902	0.001652844	-0.034
	10.1 - 12.5	26.77	22.10	0.001364913	0.001652844	-0.191
	12.6 - 15	8.10	7.65	0.001559969	0.001652844	-0.058
	15.1 - 17.5	2.81	0.96	0.000562687	0.001652844	-1.078
	17.6 - 20	0.88	0	0	0.001652844	**-0.191**
	20.1 - 22.5	0.36	0	0	0.001652844	**-0.191**
	22.6 - 25	0.16	0.48	0.004890095	0.001652844	1.085
	>25	0.14	0	0	0.001652844	**-0.191**
Lithology	Granite and other stones	15.92	28.55	0.002964327	0.001652844	0.584
	Schists and grauvaques (sandstone-schist complex)	49.02	33.21	0.001119983	0.001652844	-0.389
	Alluvium	2.47	0	0	0.001652844	**-2.706**
	Glacial deposits	0.24	0.96	0.006717045	0.001652844	1.402
	Limestones, dolomitic limestone, marly limestone and marl	7.15	0.48	0.00011041	0.001652844	-2.706
	Quartzite	4.87	21.62	0.007345645	0.001652844	1.492
	Red sandstone, conglomerates, marl and dolomitic limestones	1.89	0.60	0.000521045	0.001652844	-1.154
	Arenites, conglomerates, limestones, dolomitic limestone and marl	0.85	0	0	0.001652844	**-2.706**
	Conglomerates, arenites, limestone, dolomitic limestone, marly limestone and marl	2.69	0	0	0.001652844	**-2.706**
	Arenites, conglomerates, limestones, dolomitic limestone	4.40	0	0	0.001652844	**-2.706**
	Schists, amphibolite, mica schists, quartzite grauvaques, carboned stones and gneisses	4.71	2.15	0.00075485	0.001652844	-0.784
	Schists and grauvaques	1.68	5.97	0.00588567	0.001652844	1.270
	Sands, rocky, arenites and clay	0.66	0.12	0.000298639	0.001652844	-1.711
	Clayey schist, grauvaques and arenites	0.08	3.23	0.069057241	0.001652844	3.732
	Gabbro	0.04	0.00	0	0.001652844	-2.706
	Arenites, limestone, sand, stony banks and clay	2.94	2.87	0.00161127	0.001652844	-0.025
	Granite porphyritic	0.08	0.24	0.005235054	0.001652844	1.153
	Sands and gravel	0.30	0	0	0.001652844	**-2.706**
	Conglomerates, arenites, white limestone and red marl	0.02	0	0	0.001652844	**-2.706**
Soil	Humic Cambisols	21.98	18.88	0.001419686	0.001652844	-0.152
	Rankers	2.60	29.63	0.018817902	0.001652844	2.432
	Dystric Cambisols	9.65	0	0	0.001652844	**-1.973**
	Dystric Fluvisols	0.60	0	0	0.001652844	**-1.973**
	Eutric Lithosol	37.02	17.68	0.000789427	0.001652844	-0.739
	Calcic Cambisols	1.77	0.48	0.000447149	0.001652844	-1.307
	Calcic Luvisols	7.19	0	0	0.001652844	**-1.973**

PFM	Classes	Watershed area (%)	Landslides test area (%)	CP	PP	IV*
	Hortic Luvisols	8.10	32.74	0.00668236	0.001652844	1.397
	Chromic Cambisols	2.58	0.36	0.00022981	0.001652844	-1.973
	Eutric Cambisols	6.06	0	0	0.001652844	**-1.973**
	Calcic-chromic Cambisols	1.20	0	0	0.001652844	**-1.973**
	Hortic Podzols	1.26	0.24	0.000312905	0.001652844	-1.664
	Eutric Fluvisols	0.00	0	0	0.001652844	**-1.973**
COS	Urban fabric	2.81	0.72	0.000421079	0.001652844	-1.367
	Industrial, commercial and transport units	0.61	0	0	0.001652844	**-2.090**
	Mine, dump and construction sites	0.24	0	0	0.001652844	**-2.090**
	Artificial, non-agricultural vegetated areas	0.06	0	0	0.001652844	**-2.090**
	Arable land	4.88	0	0	0.001652844	**-2.090**
	Permanent crops	5.85	0.84	0.000236356	0.001652844	-1.945
	Pastures	1.22	0	0	0.001652844	**-2.090**
	Heterogeneous agricultural areas	7.72	0.96	0.000204535	0.001652844	-2.090
	Forests	34.03	14.34	0.000696271	0.001652844	-0.865
	Scrub and/or herbaceous vegetation associations	39.57	81.96	0.003423504	0.001652844	0.728
	Open spaces with little or no vegetation	1.68	1.19	0.001175555	0.001652844	-0.341
	Inland waters	1.32	0	0	0.001652844	**-2.090**
CLC	Urban fabric	1.19	0	0	0.001652844	**-2.253**
	Industrial, commercial and transport units	0.27	0	0	0.001652844	**-2.253**
	Mine, dump and construction sites	0.09	0	0	0.001652844	**-2.253**
	Artificial, non-agricultural vegetated areas	0.01	0	0	0.001652844	**-2.253**
	Arable land	3.41	0	0	0.001652844	**-2.253**
	Permanent crops	3.62	0	0	0.001652844	**-2.253**
	Pastures	0.08	0	0	0.001652844	**-2.253**
	Heterogeneous agricultural areas	18.20	1.91	0.000173649	0.001652844	-2.253
	Forests	26.89	22.10	0.001358648	0.001652844	-0.196
	Scrub and/or herbaceous vegetation associations	42.93	71.57	0.002755613	0.001652844	0.511
	Open spaces with little or no vegetation	2.31	4.42	0.00316411	0.001652844	0.649
	Inland waters	1.01	0	0	0.001652844	**-2.253**

*Bold values represent the values not determinable by IV method. Are equal to the lowest value find for each predisposing factor.

Anexo 3. Material suplementar do artigo Meneses *et al.* (2017), publicado no Sustainability Journal.

Table A. All statistical data collected (socioeconomic and environmental).

Variable		Description	Source
Socioeconomic	CEEA	Consumption of electric energy (kWh) – agriculture, forestry and fishing	INE
	CEED	Consumption of electric energy (kWh) – domestic	INE
	CEEI	Consumption of electric energy (kWh) – industry, construction and water	INE
	CEET	Consumption of electric energy (kWh) – total	INE
	CP	Cereals production (kg)	INE
	CRI	Crude rate of increase (%)	INE
	CTAE	Collective tourist accommodation establishments (No.)	INE
	CY	Cereals yield (kg/ha)	INE
	DRFPP	Dynamism relative factor of purchasing power (index)	INE
	ECA	Electricity consumers (No.) – agriculture, forestry and fishing	INE
	ECD	Electricity consumers (No.) – domestic	INE
	ECI	Electricity consumers (No.) – industry, construction and water	INE
	ECT	Electricity consumers (No.) – total	INE
	EI	Export intensity (%)	INE
	EMPA	Employment (No. Thousands) – agriculture, forestry and fishing	INE
	EMPI	Employment (No. Thousands) – industry, construction and water	INE
	EMPS	Employment (No. Thousands) – services	INE
	EMPT	Employment (No. Thousands) – total	INE
	GDP	Gross domestic product (€)	INE
	GPCF	Gross fixed capital formation (€)	INE
	GPE	Gross production of electricity (kWh)	INE
	GVA	Gross value added (€) – total	INE
	GVAA	Gross value added (€) – agriculture, forestry and fishing	INE
	GVAI	Gross value added (€) – industry, construction and water	INE
	GVAS	Gross value added (€) – services	INE
	OTP	Olive trees production (kg)	INE
	OTY	Olive trees yield (kg/ha)	INE
	PCGDP	Per capita Gross domestic product (€/per inhabitant)	INE
	PCPP	Per capita purchasing power (%/per inhabitant)	INE
	PES&T	Persons employed in science and technology (% of active population)	INE
	PI	Potentiality index	INE
	PPP	Proportion of purchasing power (%)	INE
	RP	Resident Population (No.)	Pordata
	VP	Vineyard production (kg)	INE
	VY	Vineyard yield (kg/ha)	INE
Environmental	EEPBL	Environmental expenditure (€) - protection of biodiversity and landscape	INE
	EEPBLPC	Environmental expenditure (€/per inhabitant) – protection of biodiversity and landscape	INE
	EET	Environmental expenditure (€) - total	INE
	EETPC	Environmental expenditure (€/per inhabitant) - total	INE
	EEWM	Environmental expenditure (€) - waste management	INE
	EEWMPC	Environmental expenditure (€/per inhabitant) - waste management	INE
	ER	Environmental revenues (€) - total	INE
	ERPBL	Environmental revenues (€) - protection of biodiversity and landscape	INE
	ERWM	Environmental revenues (€) - waste management	INE
	IWM	Investments on waste management (€) - total	INE
	UWC	Urban waste collected (t)	INE
	UWCPC	Urban waste collected per inhabitant (kg/hab)	INE
	VSW	Volumes stored by watershed (10^6 m^3)	SNIRH

INE - National Statistics Institute of Portugal; SNIRH - National System of Hydrological Resources.

Table B. LUCC in Continental Portugal between 1995 and 2007 (area in ha).

	2007																				
1995	***Pinus pinaster***	***Quercus suber***	***Eucalyptus***	***Quercus rotundifolia***	**Other *quercus***	**Other broadleaves**	***Pinus pinea***	**Other coniferous**	**Rain-fed crops**	**Irrigated crops**	**Rice**	**Vineyards**	**Olive**	**Other permanent**	**Grassland**	**Wetlands**	**Settlements**	**Shrubland**	**Other Land**	**Total**	**Unchanged (%)**	**Changes (%)**
Pinus pinaster	1057632	4679	120685	123	4177	17044	1903	933	4877	2302	0	2482	891	879	1263	187	16284	20590	1160	**1258091**	84.1	15.9
Quercus suber	2430	844962	3049	3103	109	413	4014	4	1295	856	3	466	529	34	7941	965	2191	651	180	**873195**	96.8	3.2
Eucalyptus	17751	2641	642502	1102	315	2810	1942	222	1768	2130	0	878	892	206	1065	699	7941	2577	579	**688021**	93.4	6.6
Quercus rotundifolia	166	5689	577	571613	4	45	5981	0	4241	661	1	561	925	54	11495	11494	1027	679	59	**615270**	92.9	7.1
Other *quercus*	2618	237	321	60	193227	1833	9	112	605	45	0	452	133	86	162	115	585	2231	31	**202860**	95.3	4.7
Other broadleaves	4905	436	2349	35	1762	217038	209	85	1027	410	6	578	342	691	405	498	2011	3120	54	**235963**	92.0	8.0
Pinus pinea	924	843	588	123	2	48	136056	35	317	249	2	66	23	32	368	74	1816	69	89	**141723**	96.0	4.0
Other coniferous	381	9	111	142	27	58	18	9199	6	4	0	8	4	6	23	0	56	205	32	**10289**	89.4	10.6
Rain-fed crops	23599	12603	9963	3391	6625	20481	10302	1342	983357	42627	92	22068	34037	11737	84654	3253	23788	26440	113	**1320473**	74.5	25.5
Irrigated crops	2386	237	2027	39	653	2652	461	88	23965	342217	4417	10578	3763	2844	9523	990	9526	2560	33	**418959**	81.7	18.3
Rice	1	8	3	0	0	32	25	0	757	2744	31153	21	130	103	442	66	46	16	0	**35548**	87.6	12.4
Vineyards	1299	158	874	22	145	682	212	35	13004	7447	12	166266	2035	1706	6163	90	2183	1827	22	**204181**	81.4	18.6
Olive	4010	4111	1620	807	348	1041	1696	39	13191	2150	0	5636	389151	1761	5925	976	4882	16868	34	**454246**	85.7	14.3
Other permanent	451	123	569	138	48	1204	697	10	6343	2185	29	1747	726	71732	2467	87	1799	2524	10	**92888**	77.2	22.8
Grassland	8406	25611	5404	7509	613	1886	20893	685	65861	7982	117	5435	8243	2165	422567	4030	9073	25642	345	**622468**	67.9	32.1
Wetlands	7	5	3	1	0	45	0	0	33	10	9	4	0	0	64	131185	316	21	138	**131840**	99.5	0.5
Settlements	447	53	437	115	27	188	58	51	248	87	9	30	33	22	501	217	334595	1098	48	**338264**	98.9	1.1
Shrubland	94747	10623	22273	5504	7455	53220	22025	2067	13466	1268	2	4194	4728	2401	27432	2429	13778	856344	4406	**1148361**	74.6	25.4
Other Land	1168	4	262	0	117	2209	3	43	59	38	3	19	16	5	3336	110	721	27077	68418	**103608**	66.0	34.0
Total	**1223329**	**913032**	**813617**	**593827**	**215652**	**322929**	**206505**	**14950**	**1134420**	**415412**	**35856**	**221488**	**446601**	**96464**	**585795**	**157465**	**432617**	**990541**	**75750**	**8896250**		
Unchanged (%)	86.5	92.5	79.0	96.3	89.6	67.2	65.9	61.5	86.7	82.4	86.9	75.1	87.1	74.4	72.1	83.3	77.3	86.5	90.3			
Changes (%)	13.5	7.5	21.0	3.7	10.4	32.8	34.1	38.5	13.3	17.6	13.1	24.9	12.9	25.6	27.9	16.7	22.7	13.5	9.7			
Gains (ha)	165697	68070	171115	22214	22426	105890	70449	5751	151063	73195	4702	55222	57450	24732	163228	26280	98022	134197	7333			
Losses (ha)	-200459	-28233	-45519	-43658	-9634	-18924	-5667	-1090	-337115	-76742	-4395	-37915	-65095	-21156	-199901	-656	-3669	-292018	-35190			

Overall unchanged: 84%; Overall changes: 16%; Kappa coefficient: 82.4%.

Table C. LUCC in Continental Portugal between 2007 and 2010 (area in ha).

	2010																					
2007	***Pinus pinaster***	***Quercus suber***	***Eucalyptus***	***Quercus rotundifolia***	**Other *quercus***	**Other broadleaves**	***Pinus pinea***	**Other coniferous**	**Rain-fed crops**	**Irrigated crops**	**Rice**	**Vineyards**	**Olive**	**Other permanent**	**Grassland**	**Wetlands**	**Settlements**	**Shrubland**	**Other Land**	**Total**	**Unchanged (%)**	**Changes (%)**
Pinus pinaster	1192765	1556	16438	17	800	1629	1174	220	749	406	0	646	241	153	212	15	2876	3157	276	**1223329**	97.5	2.5
Quercus suber	208	909833	760	168	56	114	493	5	66	45	1	31	89	2	376	56	232	469	29	**913032**	99.6	0.4
Eucalyptus	3270	705	802734	215	58	461	252	29	418	268	1	192	350	92	346	32	2429	1551	213	**813617**	98.7	1.3
Quercus rotundifolia	75	801	36	590742	77	74	78	1	250	35	0	156	604	1	368	138	275	106	8	**593827**	99.5	0.5
Other *quercus*	627	79	67	70	213722	322	0	9	192	8	0	100	15	14	13	11	173	225	4	**215652**	99.1	0.9
Other broadleaves	2820	175	1479	54	498	268987	54	26	372	119	0	176	49	51	96	102	612	47170	88	**322929**	83.3	16.7
Pinus pinea	288	314	134	169	8	7	204897	14	42	15	0	3	31	2	39	10	524	1	5	**206505**	99.2	0.8
Other coniferous	76	18	9	0	0	40	0	14661	3	0	0	0	20	7	0	1	24	91	0	**14950**	98.1	1.9
Rain-fed crops	752	1361	366	496	181	590	77	43	1096530	6356	61	3392	11339	983	8260	201	2139	1283	11	**1134420**	96.7	3.3
Irrigated crops	1884	19	120	3	19	30	3	6	1597	401641	2458	1097	3839	410	1142	104	977	61	2	**415412**	96.7	3.3
Rice	0	0	0	0	0	4	0	0	4	243	35547	0	38	0	2	10	7	0	0	**35856**	99.1	0.9
Vineyards	41	1	106	0	32	61	7	3	2647	1338	16	213322	716	278	2527	0	272	122	0	**221488**	96.3	3.7
Olive	57	43	319	18	10	55	42	0	2103	223	0	445	440134	121	1536	167	596	730	1	**446601**	98.6	1.4
Other permanent	146	1	16	6	3	49	17	5	797	313	0	134	431	92802	826	3	175	119	619	**96464**	96.2	3.8
Grassland	829	1645	488	886	80	245	228	70	10476	2433	168	911	5656	287	548856	480	1909	9889	260	**585795**	93.7	6.3
Wetlands	1	0	0	7	0	3	0	0	0	7	1	0	11	0	4	157399	24	7	1	**157465**	100.0	0.0
Settlements	69	0	137	6	6	18	13	13	69	80	3	21	13	10	209	610	431120	200	20	**432617**	99.7	0.3
Shrubland	5717	685	15313	245	796	1448	117	47	2244	195	8	741	871	316	3845	182	2541	954110	1118	**990541**	96.3	3.7
Other Land	167	4	373	0	5	13	0	3	6	2	0	21	26	0	99	2	135	2919	71975	**75750**	95.0	5.0
Total	**1209790**	**917239**	**838896**	**593102**	**216352**	**274150**	**207454**	**15156**	**1118568**	**413729**	**38262**	**221390**	**464472**	**95528**	**568756**	**159524**	**447040**	**1022211**	**74631**	**8896250**		
Unchanged (%)	98.6	99.2	95.7	99.6	98.8	98.1	98.8	96.7	98.0	97.1	92.9	96.4	94.8	97.1	96.5	98.7	96.4	93.3	96.4			
Changes (%)	1.4	0.8	4.3	0.4	1.2	1.9	1.2	3.3	2.0	2.9	7.1	3.6	5.2	2.9	3.5	1.3	3.6	6.7	3.6			
Gains (ha)	17025	7406	36161	2361	2631	5162	2556	495	22038	12088	2716	8067	24338	2726	19900	2125	15921	68101	2655			
Losses (ha)	-30564	-3199	-10882	-3085	-1931	-53941	-1608	-289	-37890	-13771	-309	-8166	-6467	-3662	-36939	-65	-1498	-36430	-3775			

Overall unchanged: 97.1%; Overall changes: 2.9%; Kappa coefficient: 96.6%.

Table D. LUCC in Continental Portugal between 1995 and 2010 (area in ha).

	2010																					
1995	***Pinus pinaster***	***Quercus suber***	***Eucalyptus***	***Quercus rotundifolia***	**Other *quercus***	**Other broadleaves**	***Pinus pinea***	**Other coniferous**	**Rain-fed crops**	**Irrigated crops**	**Rice**	**Vineyards**	**Olive**	**Other permanent**	**Grassland**	**Wetlands**	**Settlements**	**Shrubland**	**Other Land**	**Total**	**Unchanged (%)**	**Changes (%)**
Pinus pinaster	1038959	5839	133182	119	3965	13623	2643	1091	5232	2642	0	3145	1135	948	1434	256	19491	23083	1306	**1258091**	82.6	17.4
Quercus suber	2475	844315	3579	2888	165	500	4061	7	1115	841	4	488	683	38	7734	1041	2411	658	193	**873195**	96.7	3.3
Eucalyptus	17672	3201	638460	1293	321	2354	2139	214	1954	2355	0	945	1031	335	1329	737	9779	3221	681	**688021**	92.8	7.2
Quercus rotundifolia	213	6160	581	569696	20	105	6022	1	4048	565	1	773	1840	53	11453	11697	1225	759	59	**615270**	92.6	7.4
Other *quercus*	2296	310	370	123	193215	1512	8	125	659	50	0	539	148	90	215	136	719	2313	31	**202860**	95.2	4.8
Other broadleaves	5239	567	2716	80	1741	215288	261	95	1189	476	6	624	386	748	426	611	2376	3011	126	**235963**	91.2	8.8
Pinus pinea	894	797	632	284	2	43	135394	46	298	252	2	67	62	34	368	88	2286	80	94	**141723**	95.5	4.5
Other coniferous	402	9	115	142	26	53	18	9069	8	4	0	8	10	2	19	1	74	295	32	**10289**	88.1	11.9
Rain-fed crops	24036	13839	12717	3519	6784	20815	10260	1376	963436	45452	127	23819	45992	11953	82426	3862	26169	23774	117	**1320473**	73.0	27.0
Irrigated crops	3983	254	2170	38	678	2468	508	96	23672	335413	6820	10427	6319	2711	8978	1095	10628	2671	31	**418959**	80.1	19.9
Rice	1	17	3	0	0	35	25	0	649	2817	31065	21	356	103	311	78	51	16	0	**35548**	87.4	12.6
Vineyards	1293	163	988	10	150	619	225	40	13750	7799	27	162129	2810	1887	7735	96	2534	1910	17	**204181**	79.4	20.6
Olive	4077	4209	1632	823	371	1112	1744	40	14448	2306	0	5917	385305	1806	6777	1231	5424	16980	45	**454246**	84.8	15.2
Other permanent	450	138	612	145	50	1238	713	10	6589	2348	29	1814	887	69935	2692	96	2002	2509	629	**92888**	75.3	24.7
Grassland	8882	26640	5787	8163	706	1986	21047	722	67607	8894	155	5726	12135	2257	406356	4382	10442	30216	363	**622468**	65.3	34.7
Wetlands	5	5	6	2	0	34	0	0	33	15	10	4	0	0	61	131171	331	27	136	**131840**	99.5	0.5
Settlements	416	57	516	115	27	184	67	54	235	112	11	26	36	22	499	222	334566	1052	47	**338264**	98.9	1.1
Shrubland	97336	10713	24506	5661	8014	11949	22315	2127	13585	1349	2	4892	5321	2603	26868	2608	15725	888198	4591	**1148361**	77.3	22.7
Other Land	1162	7	10324	0	119	231	4	42	62	37	3	27	16	5	3076	116	809	21438	66131	**103608**	63.8	36.2
Total	**1209790**	**917239**	**838896**	**593102**	**216352**	**274150**	**207454**	**15156**	**1118568**	**413729**	**38262**	**221390**	**464472**	**95528**	**568756**	**159524**	**447040**	**1022211**	**74631**	**8896250**		
Unchanged (%)	85.9	92.0	76.1	96.1	89.3	78.5	65.3	59.8	86.1	81.1	81.2	73.2	83.0	73.2	71.4	82.2	74.8	86.9	88.6			
Changes (%)	14.1	8.0	23.9	3.9	10.7	21.5	34.7	40.2	13.9	18.9	18.8	26.8	17.0	26.8	28.6	17.8	25.2	13.1	11.4			
Gains (ha)	170831	72924	200435	23406	23137	58862	72060	6087	155132	78316	7197	59261	79167	25593	162400	28353	112475	134014	8500			
Losses (ha)	-219133	-28880	-49561	-45574	-9645	-20675	-6329	-1220	-357037	-83546	-4483	-42053	-68941	-22953	-216113	-669	-3699	-260164	-37477			

Overall unchanged: 83.4%; Overall changes: 16.6%; Kappa coefficient: 81.8%.

Anexo 4. Material suplementar do artigo Meneses *et al.* (2015), publicado no Science of the Total Environment Journal.

Table 4. LUCCs in Sector 1 (S1) of Zêzere watershed. Area of transitions (%) by class CLC 2000 and 2006. For the ID CLC correspondences see Fig. 3.

		CLC 2006																							
	ID	**111**	**112**	**121**	**124**	**211**	**212**	**221**	**222**	**223**	**231**	**241**	**242**	**243**	**244**	**311**	**312**	**313**	**321**	**322**	**324**	**332**	**333**	**334**	**Total**
CLC 2000	**111**	04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	04
	112	0	1.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.11
	121	0	0	0.24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.24
	124	0	0	0	06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	06
	211	0	0	02	0	8.23	05	05	0	0	0	01	02	0	0	0	0	0	03	0	0	0	0	0	8.41
	212	0	0	0	0	0	1.43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.43
	221	0	0	0	0	03	0	1.36	0	0	0	0	03	0	0	0	0	0	0	0	0	0	0	0	1.41
	222	0	0	0	0	04	0	0	2.75	0	0	03	0	0	0	0	0	0	0	0	0	0	0	0	2.81
	223	0	0	0	0	0	0	0	0	0.16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.16
	231	0	0	0	0	0	0	0	0	0	0.42	0	0	0	0	0	0	0	0	0	0	0	0	0	0.42
	241	0	0	0	0	0	0	0	0	0	0	0.16	0	0	0	0	0	0	0	0	0	0	0	0	0.16
	242	0	03	03	0	0	0	04	06	0	0	0	15.67	0	0	0	0	0	0	0	0	0	0	0	15.83
	243	0	0	0	0	01	0	01	03	0	0	0	08	7.52	0	0	0	0	0	0	0	0	0	0	7.67
	244	0	0	0	0	0	0	0	0	0	0	0	0	0	04	0	0	0	0	0	0	0	0	0	04
	311	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.99	0	0	0	0	0.23	0	0	0	2.21
	312	0	0	0	0	0	0	0	0	0	0	02	03	01	0	0	5.64	09	0	04	2.08	0	0	0.14	8.04
	313	0	01	0	0	0	0	0	0	0	0	0	02	0	0	01	0	4.79	0	03	1.41	0	0	0	6.27
	321	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10.43	0	07	0	0	0	10.51
	322	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.98	07	0	0	0	4.05
	324	0	0	01	0	0	0	0	0	0	0	0	05	0	0	0.27	0.51	0	0	0	19.85	0	0	0	20.70
	332	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0	0	0.17
	333	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.88	0	7.88
	334	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	06	0.35	0	0	0	0.41
	Total	04	1.14	0.30	06	8.31	1.49	1.46	2.84	0.16	0.42	0.22	15.90	7.53	04	2.26	6.15	4.88	10.46	4.10	24.06	0.17	7.88	0.14	100
Total Area: 70055 ha. Overall accuracy: 94%.																									

Table 5. LUCCs in Sector 2 (S2) of Zêzere watershed. Area of transitions (%) by class CLC 2000 and 2006. For the ID CLC correspondences see Fig. 3.

		CLC 2006									
	ID	**211**	**212**	**243**	**312**	**313**	**321**	**322**	**324**	**512**	**Total**
CLC 2000	**211**	0.91	0	0	0	0	0	0	0	0	0.91
	243	0	0	2.29	0	0	0	0	0.36	0	2.64
	312	0	0	0	8.58	0	0	0	19.79	0	28.37
	313	0	0	0	0	0.77	0	0	2.74	0	3.50
	322	0	0	0	0	0	0	18.24	0.63	0	18.86
	324	0	0	0	0.54	0	0	0	41.24	0	41.78
	512	0	0	0	0	0	0	0	0	3.93	3.93
	Total	0.91	0	2.29	9.12	0.77	0	18.24	64.74	3.93	100
Total Area: 4937 ha. Overall accuracy: 76%.											

Table 6. LUCCs in Sector 3 (S3) of Zêzere watershed. Area of transitions (%) by class CLC 2000 and 2006. For the ID CLC correspondences see Fig. 3.

		CLC 2006																											
	ID	112	121	122	131	132	142	211	212	221	222	223	231	241	242	243	244	311	312	313	321	322	323	324	332	333	334	511	512	Total
CLC 2000	112	0.62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.62
	121	0	0.10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.10
	131	0	0	0	03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	03
	132	0	0	0	0	02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	02
	133	0	02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	02
	142	0	0	0	0	0	01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	01
	211	0	0	0	0	0	0	1.96	0	0	02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.99
	212	0	0	0	0	0	0	0	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.75
	221	0	0	0	0	0	0	0	0	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14
	222	0	0	0	0	0	0	0	0	0	0.37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.37
	223	0	0	0	0	0	0	0	0	0	0	0.60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.60
	231	0	0	0	0	0	0	0	0	0	0	0	03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	03
	241	01	0	0	0	0	0	0	0	0	0	0	0	2.37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.38
	242	0	0	0	0	0	0	0	0	0	0	0	0	0	5.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.34
	243	0	01	0	0	0	0	01	0	0	0	0	0	0	03	5.09	0	01	02	01	0	0	0	0.16	0	0	0	0	0	5.35
	244	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	06	0	0	0	0	0	0	0	0	0	0	0	0	06
	311	0	01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.55	06	05	0	0	0	2.26	0	0	04	0	0	6.97
	312	01	01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	03	17.11	04	01	01	0	17.41	0	0	09	0	0	34.73
	313	01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	02	04	6.34	0	0	0	2.06	0	0	05	0	0	8.53
	321	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.43	0	0	0	0	0	0	0	0	0.43
	322	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.12	0	09	0	0	0	0	0	3.21
	323	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.24	0	0	0	0	0	0	0.24
	324	0	01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.36	1.99	0.43	0	0	0	19.78	0	0	0.20	0	0	23.79
	332	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	04	0	0	0	0	04
	333	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.12	0	0	0	1.12
	334	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	01	0	0	0	1.50	0	0	0.13	0	0	1.64
	511	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	06	0	06
	512	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.45	1.45
	Total	0.64	0.16	01	03	02	01	1.97	0.75	0.14	0.40	0.60	03	2.38	5.38	5.10	06	5.97	19.21	6.88	0.44	3.13	0.24	43.27	04	1.12	0.52	06	1.45	100

Total Area: 321453 ha. Overall accuracy: 72%.

Table 7. LUCCs in Sector 4 (S4) of Zêzere watershed. Area of transitions (%) by class CLC 2000 and 2006. For the ID CLC correspondences see Fig. 3.

		CLC 2006																									
	ID	111	112	121	122	124	131	132	133	142	211	212	221	222	223	241	242	243	311	312	313	321	323	324	334	511	512	Total
CLC 2000	111	07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	07
	112	0	2.75	01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.75
	121	0	0	0.28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.28
	124	0	0	0	0	03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	03
	131	0	0	0	0	0	0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15
	133	0	0	0.16	0	0	0	0	04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.20
	142	0	0	0	0	0	0	0	0	03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	03
	211	0	0	0	0	0	0	0	0	0	0.69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.69
	212	0	0	0	0	0	0	0	0	0	0	0.79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.79
	221	0	0	0	0	0	0	0	0	0	0	0	1.20	0	0	0	02	0	0	0	0	0	0	0	0	0	0	1.23
	222	0	0	0	0	0	0	0	0	0	0	0	0	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0.12
	223	0	0	0	0	0	0	0	0	0	0	0	0	0	9.13	0	0	0	0	0	0	0	0	0	0	0	0	9.13
	241	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.29	0	0	0	0	0	0	0	0	0	0	0	7.30
	242	0	02	01	0	0	0	0	0	0	0	0	02	0	0	06	10.35	0	0	0	0	0	0	01	0	0	0	10.46
	243	0	0	0	0	0	0	0	0	0	0	0	0	0	0	01	01	13.07	01	0	0	0	0	09	0	0	0	13.19
	311	0	0	0	03	0	0	0	0	0	0	0	0	0	01	0	0	0	3.82	0	06	0	0	2.26	0	0	01	6.19
	312	0	01	0	0	0	03	0	0	0	0	0	01	0	0	0	0	0	03	7.18	04	0	02	3.97	0.10	0	0	11.40
	313	0	0	01	0	0	01	0	0	0	0	0	0	0	0	01	0	01	07	01	9.20	0	0	4.73	0.13	0	02	14.20
	321	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.23	0	0	0	0	0	1.23
	323	0	0	0	0	0	02	0	0	0	0	0	0	0	0	0	01	0	0	0	0	0	7.25	0	0	0	0	7.28
	324	0	01	01	0	0	0	0	02	0	0	0	01	0	0	01	0	01	0.44	0.28	04	0	02	12.16	0.28	0	0	13.29
	511	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	01	0	01
	512	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	01	01
	Total	07	2.79	0.48	03	03	0.21	0	05	03	0.69	0.79	1.23	0.12	9.13	7.39	10.39	13.09	4.38	7.47	9.34	1.23	7.30	23.22	0.51	01	03	100

Total Area: 109941 ha. Overall accuracy: 87%.